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THE ORIGIN OF PRIMARY LEAD ORES.

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ABSTRACT.

Lead concentrated in ore deposits is called *common lead* or *ore-lead*. Its standard atomic weight (1936) is 207.21. The lead dispersed through rocks in minute quantities is called *rock-lead*. Rock-lead consists partly of common lead, which was originally present in the rock-material; and partly of *radiogenic lead*, which has been generated in the same rock-material as a result of the radioactive disintegration of uranium and thorium during geological time, the duration of which is now taken to be about 2,000 million years. From the available determinations of lead, uranium, and thorium in various rocks it is shown: (*a*) that the average atomic weight of granitic rock-lead should have progressively decreased during geological time from 207.21 at the beginning to 207.14 at the present day; (*b*) that the average atomic weight of basaltic rock-lead should have similarly decreased from 207.21 to 207.10. The atomic weight of rock-lead concentrated in the sublimate mineral, cotunnite, from the 1906 magma of Vesuvius, is 207.05, a result which confirms the inference that rock-lead has an atomic weight significantly lower than that of common lead. The atomic weight of ore-lead, however, is found to be $207.21 \pm .01$, and—as far back as 1,300 million years—to be independent of the geological age of the ore. It follows from the evidence presented that ore-lead has not been derived from granitic or basaltic rocks, or from the sediments formed from such rocks, and that it has no genetic connection with acid or basic magmas. Ore-lead must therefore have ascended from depths below the sialic and basaltic layers of the lithosphere. Gregory's hypothesis that "the source of the ores appears to lie in a zone deeper than that of the ordinary igneous rocks" is thus largely confirmed, so far as lead ores are concerned. The data for peridotites, however, are too few as yet to justify the extension of this important generalisation to ultrabasic rocks and magmas.

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HISTORICAL INTRODUCTION.

At the present time it is safe to say that a large majority of students of ore deposits believe that the metalliferous contents of mineral veins that are associated with igneous rocks of approximately the same geological age have been derived—by one process or another—from the magmas of those rocks. The names of the leading workers who have developed this hypothesis make an imposing list, including, as they do, the following: J. L. Heim (1806); Daubrée (1841); Elie de Beaumont (1847); Stelzner (1879); Vogt (1893); Kemp (1902); Lindgren (1907); and many others. So strong is the circumstantial evidence in favour of this view, that where similar mineral veins are found without visible igneous associates (*e.g.* telethermal deposits) it has commonly been supposed that the igneous representatives of an assumed magmatic source are not actually missing, but lie hidden at crustal levels still uncovered by denudation. The galena—zinc blende—fluorite—barite assemblage provides many well known examples of ore complexes unassociated with visible igneous rocks. Other investigators, however, have seen in such occurrences evidence that the ores concerned (and, by analogy, many others) were not of direct magmatic origin, but were derived by some form of "lateral secretion" from the surrounding country rocks. The advocates of this hypothesis, who naturally extended its application to igneous as well as sedimentary rocks, include Bischoff (1847); Sandberger (1882); Van Hise (1901); and Rickard (1908). It is to be noted that even on this hypothesis the ore substances are still of ultimate igneous origin.

At the most, a sedimentary cycle—or a series of such cycles—has been introduced between the period of ascent into the upper levels of the crust and the period of concentration into veins.

A much more limited group of workers have followed the lead of Descartes (1644), who held the view that "below the stony outer crust of the earth, there was a shell of very heavy matter from which came the metallic minerals found in veins traversing the outer crust. He inferred that these vein minerals represented material that had been driven outwards as exhalations towards the surface by the earth's internal heat, and deposited in the fissures of the cooled outer crust" (Crook, p. 27).[1] Pošepný (1893) and de Launay (1893) also considered that the metalliferous substances were extracted from a deep-seated substratum or "barysphere," but they differed from Descartes in introducing the idea that the ore materials were transported to the upper part of the crust by the magmas of eruptive rocks, whence, in turn, they were concentrated and deposited by thermal waters. Gregory (1906), however, returned to the pure exhalation hypothesis of Descartes and dispensed altogether with the magmas of igneous rocks. "The source of the ores," he writes (1928, p. 19), "appears to lie in a zone deeper than that of the ordinary igneous rocks. . . . The surface of the barysphere is probably irregular, and peaks rise from it into the lithosphere and upraise the overlying ore-zone to a level at which they feed the lodes." The common association of ores with igneous rocks is ascribed to the fact that intrusions rupture the crust and so provide fractures and fissures through which the ore solutions can readily ascend. The ores are not regarded as comagmatic with the associated igneous rocks.

Referring to this view, Crook (p. 18) remarks: "It is, indeed, puzzling to understand how anyone can find adequate geological grounds for this hypothesis." But geological support is not lacking. The fact is, at least for many classes of ores, that certain crustal belts (whether igneous or sedimentary) are richly accompanied by ores, whereas others, or other parts of the same

[1] References in parenthesis refer to bibliography at end of paper.

belts, are disappointingly lacking in mineral wealth. Both Pošepný and de Launay fully realised the significance of this low correlation factor, since they felt it necessary to get the ores into their magmas from an underlying source which might or might not be tapped, according to local conditions. Gregory evidently found the geological grounds both adequate and conclusive. With regard to lead ores, with which this paper is to be specifically concerned, he made his position clear beyond all possibility of ambiguity. He writes as follows (1928, p. 108): "The lead ores illustrate the independence of lodes of the country rock. In many areas as in Great Britain, the Linares region of Spain, and the Rocky Mountains, the ordinary lodes of lead are strikingly similar in composition and essential features, whether they occur in granite, slate, sandstone, or limestone. The ores at Coeur d'Alene in Idaho and Leadville in Colorado, for example, are remarkably alike, in spite of the differences in structure between the two fields. This similarity indicates that the ores are not derived from either the adjacent sedimentary or intrusive rocks, but come from an ore-zone beneath the igneous rocks of the crust. Like the plutonic waters they work their way upward through igneous and sedimentary rocks alike."

In 1926 I attacked the problem from the standpoint of geochemistry and atomic weights, and presented evidence leading to the conclusion that "the ore bodies in which galena occurs are not derivatives from the igneous rocks visibly associated with them in time and place" (Holmes, 1926, p. 482). On the data then available for the average amounts of lead (Clarke and Steiger, 1914), uranium, and thorium in igneous rocks, I showed that roughly half the lead dispersed through igneous rocks and their magmas would be of radioactive origin, the radiogenic lead consisting of a mixture of uranium-lead and thorium-lead with an average atomic weight of about 206.9. The atomic weight of common lead, that is, of commercial lead from galena and other common ores, was always found to be about 207.2, whatever its source. If the remaining half of the lead in igneous rocks were also common lead, then the atomic weight of the total

rock-lead would be about 207.05. It thus seemed clear that if ore-lead represented a local concentration of rock-lead its atomic weight would vary, according to the geological age of its source, very much more than it actually appeared to do.

In 1929 I summarised the evidence showing that the atomic weight of ore-lead is independent of the period of mineralization. I also drew attention to a determination of the atomic weight of lead from the sublimate mineral, cotunnite (lead chloride). Cotunnite originated during the 1906 eruption of Vesuvius and could, therefore, be reasonably regarded as a mineral formed from a naturally isolated sample of rock-lead. The mean result obtained by the investigators, Piutti and Migliacci (1923), was 207.05. At the time when it was obtained, this apparently abnormal value could not be adequately accounted for, though the authors pointed out that it corresponded with the atomic weight of a mixture of common lead with 12 per cent of uranium-lead. With the recognition that the lead was rock-lead from the leucite-tephrite magma of Vesuvius, the low atomic weight ceased to be inexplicable.

Two years later the precise determinations of the lead contents of various rocks carried out by Hevesy and Hobbie (1931) became available. These results showed that the average value found by Clarke and Steiger (7.5×10^{-6} gram of lead per gram of rock) was too small to be representative; the new average being 16×10^{-6} gram per gram. Moreover, Hevesy and Hobbie obtained the figure 30×10^{-6} gram per gram for a composite sample of 58 granitic rocks. The latter included Pre-Cambrian, Caledonian and Hercynian granites from various parts of Europe (ranging petrographically from granite to granodiorite) and similar North American rocks of various ages from Pre-Cambrian to Tertiary. With this new data I showed that "if the atomic weight of the lead originally present in the earth be taken as 207.22, then that of the lead now present in granitic rocks should have a value near 207.19. Thus if lead ores have been derived from granitic magmas the atomic weight of ore-lead should vary between 207.22 and 207.19 according to the age,

the higher value referring to ores dating from the beginning of geological time and the lower to ores formed at the present day." Since determinations made since 1915 did, in fact, range between 207.22 and 207.18, I was obliged to conclude that the evidence then available was inconclusive, always provided that the age of the earth was not considerably greater than 1,600 million years, this having been the age adopted in all the calculations made until then.

Since 1931 much new atomic weight evidence has accumulated, more especially of samples of lead of known provenance and geological age. Moreover, the atomic weights of uranium-lead and thorium-lead are more accurately known; there are more determinations of uranium and thorium in rocks; and the age of the earth is now known to be considerably greater than 1,600 million years. The time has therefore come to review afresh the available data bearing on the distinction between ore-lead and rock-lead and on the possibility of the metallogenic independence of these types of lead.

GEOLOGICAL TIME.

The oldest rocks of the earth's crust so far recognized and adequately dated occur in south-east Manitoba, east of Lake Winnipeg (Wright, 1932, pp. 12–47). The sequence of formations and igneous rocks representing the Manitoban orogenic cycle is listed in Table I, together with the sequences in the later cycles of South Dakota, Athabasca and Great Bear Lake. The dates inserted in the table are calculated from lead-ratios which have been corrected for the effect of the actino-uranium series on the assumption that the half-life of actino-uranium is about one tenth that of uranium I. If this correction were not made, the ages would be considerably higher.[2] It may be noted that all the rocks referred to are much older than the pegmatites of the Laurentian cycle, those of Manitoba being 700 million years older.

The oldest rocks of Manitoba provide a clear demonstration of the statement that no evidence of the earth's beginning has yet

[2] For data and details of calculations see Holmes, 1937, pp. 153 and 204–206.

been detected in any part of the world. The sediments and volcanic rocks of the Rice Lake system have been invaded from below by granite-making magmas or emanations and transformed, in part, into schists and migmatites. Thus, the visible foundations of the area are crystalline rocks that are younger than the sediments, in the sense that the foundation rocks crystallised after

TABLE I.

PRE-LAURENTIAN OROGENIC CYCLES OF NORTH AMERICA.

GREAT BEAR LAKE AREA	LAKE ATHABASCA AREA	BLACK HILLS, SOUTH DAKOTA
Mineralisation (1,210–1,390 m.y.)	Mineralisation (1,300 m.y.)	Mineralisation (1,330, m.y.)
Pegmatites and Granites	Pegmatites and Granites Peridotite and Basic Rocks	Harney Peak Granite (1,350 m.y.)
ECHO BAY System *Base not seen*	BEAVERLODGE System	(?) LEAD System
	Pegmatites and Granites	Game Lodge Granite (1,580 m.y.)
	TAZIN System	ESTES System
		NEMO System
	Base not seen	*Base not seen*

SOUTH-EAST MANITOBA

Pegmatites (1,750–1,770 m.y.)
Granites and Migmatites
Peridotites and Basic Rocks

RICE LAKE System
Wanipigow phase: Quartzite, graywacke, arkose, slate.
Beresford Lake phase: Mainly volcanic.
Manigotagan phase: Quartzite, conglomerate,* graywacke, slate.
Base not seen *

* Older rocks, not yet discovered in situ, are represented by pebbles of granitic and quartzose rocks found in the Manigotagan conglomerate.

the sediments had accumulated. Yet obviously there must have been older rocks, to provide the material of the sediments and to serve as their original basement. Bits of such older rocks still survive, as pebbles in the Manigotagan conglomerate. It is obvious that the age of the earth must be greater than 1,750 million years by at least the time required for the deposition of the Rice

Lake system and for the formation of the pre-existing rocks to which the Manigotagan pebbles bear witness. Judged by the duration of other orogenic cycles, that of the Manitoban cycle may well be of the order 150–200 million years. In round figures 2,000 million years is clearly indicated as a possible figure for the age of the earth, provided it be kept in mind that this may be a minimum estimate.

Other estimates which have a bearing on the problem may be rapidly passed in review (Holmes, 1937). The eccentricity of the orbit of Mercury suggests that the age of the solar system is between 1,000 and 10,000 million years, but probably nearer the lower limit than the higher. The tidal theory of the recession of the moon from the earth suggests that the age of the earth-moon system is less than 4,000 million years. Iron meteorites, some of which come from beyond the solar system, appear to have originated about 2,000 million years ago. The recession of the galactic nebula beyond the Milky Way is interpreted to mean that the universe has required about 2,000 million years to expand from a small region of space to its present dimensions.

The remarkable convergence of evidence strongly suggests that earth, solar system, meteorites, and galaxies, all came into existence about the same time—some 2,000 million years ago.

THE NATURE OF ROCK-LEAD.

Common lead is the ordinary lead of commerce, which is the *ore-lead* obtained from galena, cerussite, and other ores of lead. In 1936 the standard atomic weight of lead was reduced from 207.22 to 207.21.

Radiogenic lead is lead generated from the radioactive elements, uranium and thorium. Uranium-lead is a mixture of the isotopes Pb^{206} from uranium I and Pb^{207} from actino-uranium, together with minute quantities of other isotopes of smaller mass numbers, the exact source of which is not yet thoroughly established (Piggot, 1933). Fortunately the complexity of the isotopic mixture which constitutes uranium-lead need not introduce

any complication, as several excellent determinations of the atomic weight of uranium-lead are now available. These are listed in Table II and they make it clear that the atomic weight is (*a*) independent of geological age, and (*b*) not greater than 206, though it may be slightly lower. In the subsequent calculations the value 206 is adopted for uranium-lead. Thorium-lead is mainly Pb^{208}, also possibly accompanied by isotopes of lower mass number (Piggot, 1933). On the chemical scale the atomic weight of thorium-lead is now taken as 207.96 (Baxter and Alter, 1935, p. 471). This may also be slightly high, but the atomic weight of lead from the Permian thorite of Brevig, given in the table, shows that 207.96 is about right.

TABLE II.

ATOMIC WEIGHT DETERMINATIONS OF URANIUM-LEAD AND LEAD FROM THORITE.

Source of Lead *Locality*	Uranium *per cent*	Thorium *per cent*	Atomic Weight *Investigators*	Age in Millions of Years
Cyrtolite, *Bedford, New York.*	7.29	None	205.93 *Baxter and Alter, 1935*	380
Kolm, *Güllhögen, Sweden.*	1.24	None	206.01 *Baxter and Bliss, 1930*	420
Pitchblende, *Katanga.*	*ca* 75	None	205.996 *Baxter and Alter, 1935*	580
Uraninite, *Morogoro.*	*ca* 75	*ca* .3	206.03 *Hönigschmid et aliter, 1933*	610
Pitchblende, *Great Bear Lake.*	51.536	.004	205.99 *Marble, 1936*	1,210
Thorite, *Brevig, Norway.*	.45	30.10	207.90 *Hönigschmid, 1919*	220

Rock-lead is a mixture of common lead with (on an average) the radiogenic lead generated in the rock material during geological time. Hevesy and Hobbie (1931) have determined the lead in various samples of igneous rocks, representing in all 221 rocks, with the following results:

TABLE III.

LEAD CONTENT OF IGNEOUS ROCKS.

Rock Types	Grams of Lead per 10^6 Grams of Rock
Basalt, Giant's Causeway	4
Gabbros and related types (composite of 67 samples)	5
Essexites and related types (composite of 40 samples)	10
Shonkinites (average of 2 samples)	10
Soda-granites and Soda-syenites (composite of 26 samples)	11
Potash-granites and Potash-syenites (composite of 24 samples)	14
Amphibolite, xenolith in kimberlite, Wesselton Mine, South Africa	15
Kimberlite, dyke from 1,350-foot level, Dutoitspan	16
Lherzolite, Baltimore, Maryland	19
Granitic rocks (composite of 58 samples)	30
Dunite, Jackson Co., North Carolina	42
Average (221 samples)	16

At the time when the crust of the earth consolidated, all the isotopes of lead then existing must have already become mixed together to form common lead. From that time onwards radiogenic lead began to accumulate as an independent and unevenly distributed dispersion. Only under conditions of fusion or solution would the old and new isotopes again mix together, but the resulting mixture would in general, as we shall see, no longer have the atomic weight of common lead. Thus, although a rock, as such, may be of any geological age, it is the *material* of the rock with which we are concerned, and the age of this material for the purposes of the present problem is that of the age of the earth. It will be assumed in the following calculations that 2,000 million years have elapsed since the original common lead of rock-material began to be contaminated by radiogenic lead.

ATOMIC WEIGHTS OF ROCK-LEAD.

Rock-lead from Granitic Rocks.—In order to find the average atomic weight of radiogenic lead in, say, granitic rocks, the average ratio of thorium to uranium in such rocks must be determined. It is already well known that for various classes of rocks this ratio varies from 1.6 to 2.4 (Holmes, 1929). To determine it more exactly for granitic rocks in particular, all the available analytical data for thorium and uranium (expressed, as

usual, in terms of radium) have been plotted in Fig. 1. The line representing the averages at different concentrations shows that the ratio Th/Ra is $1 \times 10^{-5}/2 \times 10^{-12}$, whence the ratio Th/U is 10/6 or 1.7. The lead-generating capacity of thorium is .36 that of uranium, corresponding to the fact that, at present, the half-life period of thorium is nearly three times as long as that of the half-life period of uranium. Thus, it follows that the value of the ratio of thorium-lead to uranium-lead now being

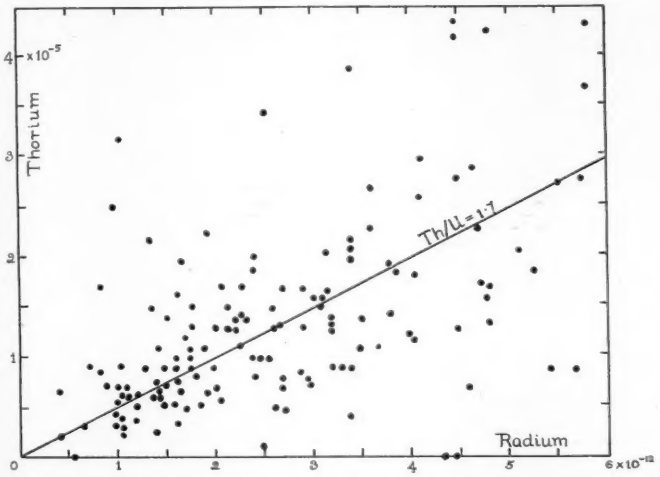

FIG. 1. Diagram representing the distribution of thorium and radium in granitic rocks.

generated in granitic rocks is $1.7 \times .36 = .61$. The average atomic weight of radiogenic lead now being generated in granitic rocks is therefore $(.61 \times 207.96 + 1 \times 206)/1.61 = 206.74$.

Various estimates of the average amounts of uranium and thorium in granitic rocks have already been published. The data plotted in Fig. 1 give the following averages:

Uranium $= 6 \times 10^{-6}$ gram per gram of average granitic rock.
Thorium $= 10 \times 10^{-6}$ gram per gram of average granitic rock.

These figures are slightly smaller than previous estimates, because a few samples of granite have been found to contain higher proportions of the radioactive elements than those falling within the scope of the diagram. Adopting the averages given above, it can be calculated that they imply the generation of 3.8×10^{-6} gram of radiogenic lead in 2,000 million years. Allowance has been made in this calculation, not only for the wearing out of the radioactive elements during geological time, but also for the fact that actino-uranium disintegrates more rapidly than uranium I, probably ten times as fast.

From the determinations of Hevesy and Hobbie the total amount of lead in average granitic rock is known. We thus have the following data:

Total rock-lead $= 30 \times 10^{-6}$ gm./gm.,
Radiogenic lead $= 3.8 \times 10^{-6}$ gm./gm. (the atomic weight of that now being generated being 206.74),
Common lead $= 26.2 \times 10^{-6}$ gm./gm. (of atomic weight 207.21),

from which it is easily calculated that the average atomic weight of granitic rock-lead would be 207.15, if the radiogenic lead had not varied in atomic weight throughout geological time.

To take into consideration the variation referred to, it will suffice for our problem to calculate the atomic weight of the radiogenic lead that was being generated 2,000 million years ago. At that time the ratio Th/U was only .62 of its present value. The average atomic weight of radiogenic lead then being generated in granitic rocks was therefore $(.62 \times .61 \times 207.96 + 206)/(1 + .62 \times .61) = 206.54$. The average of 206.54 and 206.74 is very nearly the average atomic weight of the total lead generated in granitic rocks during geological time. Adopting this average, 206.64, the average atomic weight of granitic rock-lead works out at 207.14.

Rock-lead from Basaltic Rocks.—The analytical data for radium and thorium in basaltic rocks are plotted in Fig. 2. The ratio Th/Ra seems to vary somewhat with the concentration, but

on an average it is about $.43 \times 10^{-5}/.6 \times 10^{-12}$, corresponding to $Th/U = 2.4$, which agrees well with all earlier estimates. On present-day figures, the ratio of thorium-lead to uranium-lead is thus $2.4 \times .36 = .86$. The average atomic weight of radiogenic lead now being produced in basaltic rocks is therefore $(.86 \times 207.96 + 206)/1.86 = 206.91$. For radiogenic lead being

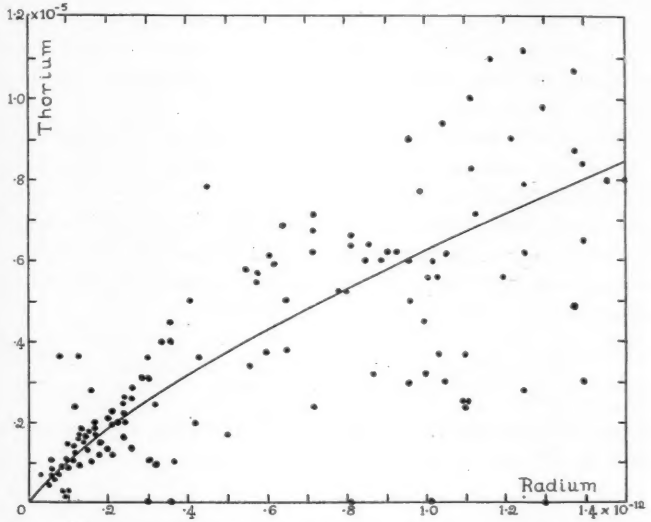

FIG. 2. Diagram representing the distribution of thorium and radium in basaltic rocks.

produced 2,000 million years ago, the corresponding atomic weight is 206.68. The average for geological time is therefore 206.80.

From the data in Fig. 2 the average amounts of uranium and thorium in basaltic rocks are:

Uranium $= 1.8 \times 10^{-6}$ gram per gram of average basaltic rock.
Thorium $= 4.3 \times 10^{-6}$ gram per gram of average basaltic rock.

These amounts imply the generation of 1.34×10^{-6} gram of radiogenic lead in 2,000 million years.

From the determinations of Hevesy and Hobbie the total amount of lead in average basaltic rock is known. Thus, the data are:

Total rock-lead $= 5 \times 10^{-6}$ gm./gm.,
Radiogenic lead $= 1.34 \times 10^{-6}$ gm./gm. (of average atomic weight 206.80),
Common lead $= 3.66 \times 10^{-6}$ gm./gm. (of atomic weight 207.21),

from which it is calculated that the average atomic weight of basaltic rock-lead is 207.10.

Rock-lead from Peridotites.—The data referring to peridotites are not yet sufficiently representative to justify the drawing of any conclusions from such calculations as the above. As shown previously, the lead contents of only three ultrabasic rocks are known, the average value being 26×10^{-6} gm./gm. If this average be adopted, for want of a better, the following results are obtained:

Uranium $= 1.5 \times 10^{-6}$ gram per gram of average peridotite.
Thorium $= 3.1 \times 10^{-6}$ gram per gram of average peridotite.

(For data see Holmes, 1933; Holmes and Paneth, 1936; Jeffreys, 1936.) Th/U = 2.07. .36 Th/U = .745.

Atomic weight of radiogenic lead now being generated = 206.84.
Atomic weight of radiogenic lead being generated 2,000 m. y. ago = 206.62.

Average atomic weight of radiogenic lead = 206.73.

Total rock-lead $= 26 \times 10^{-6}$ gm./gm.,
Radiogenic lead $= .65 \times 10^{-6}$ gm./gm. (of average atomic weight 206.73),
Common lead $= 25.35 \times 10^{-6}$ gm./gm. (of atomic weight 207.21),
Average atomic weight of rock-lead in peridotites = 207.20.

For dunite alone, the atomic weight of rock-lead is 207.205, but this result is of little interest, since it is based on a single de-

termination of lead, and only a pair of determinations of uranium and thorium.

Average Uranium Content of Igneous Rocks.—The averages here adopted for uranium give the following result for average igneous rock:

Acid rocks (136 samples)	6.0×10^{-6}	gm./gm.
Basic rocks (132 samples)	1.8×10^{-6}	gm./gm.
Ultrabasic rocks (17 samples)	1.5×10^{-6}	gm./gm.
Weighted Average	3.79×10^{-6}	gm./gm.

The validity of the above averages may be checked by comparison with a result obtained by Paneth and Koeck (1931). These investigators determined the uranium content of a composite sample of 282 specimens prepared by Hevesy and including many of the rocks in which lead had been determined. The composite sample included equal parts by weight of 133 granites, 9 quartz-diorites, 35 diorites, 82 gabbros and norites, and 23 peridotites. The determination gave 3.84×10^{-6} gram uranium per gram, in close agreement with the average of the data here used.

Rock-lead from Vesuvius.—Rock-lead has not been isolated in the laboratory in sufficient quantity for (as yet) an atomic weight determination, and indeed, to separate an adequate amount for the application of chemical methods would be a herculean task. Thus the atomic weights calculated for various kinds of rock-lead cannot be experimentally checked at the moment. But Vesuvius has carried out the required isolation on a sufficient scale. The lead of cotunnite was sublimed as chloride during the 1906 eruption and its atomic weight was found by Piutti and Migliacci (1923) to be 207.05, this result being the mean of five results ranging from 207.025 to 207.079. For a sample of common lead the same workers found a mean value (four determinations) of 207.192. In these determinations the bromide method, which generally gives slightly lower results than the chloride method, was used. The atomic weight of Vesuvius-lead is of great value in confirming the inference here drawn, that, on an average, the

atomic weight of rock-lead is significantly lower than that of common lead.

ATOMIC WEIGHTS OF ORE-LEAD.

It follows from the data summarised above that the atomic weight of ore-lead should vary, according to the geological age of the ore:

(*a*) from 207.21 to 207.14, if it be a derivative from acid rocks or magmas;
(*b*) from 207.21 to 207.10, if it be a derivative from basic rocks or magmas;
(*c*) from 207.21 to 207.20 (assuming the data to be representative, which they are probably not), if it be a derivative from ultrabasic rocks or magmas.

The actual atomic weights of ore-lead of known provenance and geological age are listed in Table IV. All the determinations are based on the ratio $PbCl_2/Ag$ and are therefore strictly comparable. The data show conclusively that there is no systematic variation of atomic weight with the period of ore deposition. The contrast between the practically constant atomic weight of ore-lead and the varying atomic weights of granitic and basaltic rock-lead is graphically shown by Fig. 3. It may be noted that the data for ore-lead are thoroughly representative, since they obviously correspond very closely with the value 207.21 now adopted as "standard," a value based on many other determinations made on common lead, but of unspecified provenance.

It might be suggested that Tertiary ore-lead is composed of common lead plus radiogenic lead in just the right proportions to give an atomic weight of $207.21 \pm .01$. On this hypothesis Pre-Cambrian lead would have an atomic weight considerably higher than this value. Actually, however, there is not the slightest indication of such a variation, and indeed Marble's determination of the lead from Great Bear Lake galena, the oldest yet in-

TABLE IV.

ATOMIC WEIGHTS OF SAMPLES OF ORE-LEAD OF KNOWN GEOLOGICAL AGE.

Source of Lead *Locality*	Geological Age (in m.y.)	Atomic Weight *Investigators*
Wulfenite and Vanadinite, *Tucson Mountains, Arizona.*	Miocene 25	207.22 *Baxter and Grover, 1915*
Cerussite, *Wallace, Idaho.*	Late Cretaceous 80	207.21 *Baxter and Grover, 1915*
Cerussite, *Wallace, Idaho.*	Late Cretaceous 80	207.21 *Baxter, Faull and Tuemmler, 1937*
Lead-silver ore, *Cœur d'Alene, Idaho.*	Late Cretaceous 80	207.218 *Baxter and Bliss, 1930*
Lead-silver ore, *Cœur d'Alene, Idaho.*	Late Cretaceous 80	207.212 *Baxter and Alter, 1933*
Galena, *Metalline Falls, Washington.*	Late Cretaceous 80	207.21 *Baxter and Grover, 1915*
Galena, *Tetüche, U. S. S. R.*	Permian 220	207.216 *Hecht and Kroupa, 1936*
Galena, *Joplin, Missouri.*	Late Carboniferous 230	207.22 *Baxter and Grover, 1915*
Cerussite, *Commern, Eifel, Germany.*	Carboniferous 240	207.20 *Baxter and Grover, 1915*
Galena, *Grube Holzappel, Nassau, Germany.*	Carboniferous 240	207.21 *Baxter and Grover, 1915*
Galena, *Yancey Co., North Carolina.*	Late Pre-Cambrian 600	207.209 *Baxter and Alter, 1935*
Cerussite, *Broken Hill, N. S. W.*	Pre-Cambrian 950	207.21 *Baxter and Grover, 1915*
Galena, *Great Bear Lake, Canada.*	Pre-Cambrian 1,300	207.205 *Marble, 1937*

vestigated, gave only 207.205, which is a trifle lower than the standard figure. The assumption tacitly made throughout this paper, that the atomic weight of common lead at the beginning of geological time was not significantly different from 207.21 is thus completely justified.

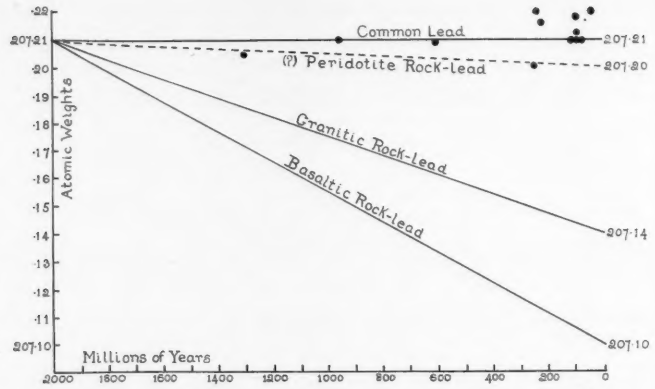

FIG. 3. Diagram showing the atomic weights of various samples of ore-lead (black dots) of known geological age, for comparison with the varying atomic weights, according to geological age, of average types of rock-lead.

CONCLUSIONS.

The proof is complete that ore-lead cannot be a concentration from either granitic or basaltic rocks, or from their respective magmas. Nor can it be a derivative from the sediments formed from such rocks. Since ore-lead has no genetic connection with either acid or basic magmas, it must have ascended from some source lying below the granitic and basaltic layers of the lithosphere. Whether that source also underlies the peridotite layer that is assumed to form the lower levels of the lithosphere cannot be decided with equal confidence. The data are mildly unfavorable to peridotite as a potential source, but obviously they are not sufficiently representative to warrant a definite inference. The point is, however, of little more than academic interest, since there is no evidence, either from the rock-associations of lead ores or from the ore-associations of peridotites, to suggest any direct genetic connection between lead ores and peridotites. Where peridotites do occur in regions characterised by lead ores, they are always older than the associated acid and basic rocks, and

these in turn (apart from occasional lamprophyres) are older than the ores.

In the light of the very cogent evidence that has been presented, the conclusion should no longer be evaded that the lead of ore bodies such as those in which galena commonly occurs cannot have originated either by any process of magmatic differentiation or by any process of "lateral secretion." Moreover, if this be true of galena, it is only reasonable to regard it as equally true of the associated sulphide minerals, including those of silver, zinc, copper and (in part) iron, and of such associated elements as fluorine and barium. For such deposits no alternative to the emanation theory of Descartes appears to be tenable. Pošepný and de Launay may have been correct in assuming that such elements as these passed into silicate magmas from a deeper source, but they were wrong in supposing that they could ever be re-extracted by thermal waters on a sufficient scale to give rise to ore bodies. Gregory alone seems to have been right—at least for certain deposits—in his heretical view that "the source of the ores appears to lie in a zone deeper than that of the ordinary igneous rocks."

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UNIVERSITY OF DURHAM, ENGLAND.
June 8, 1937.

BIBLIOGRAPHY.

BAXTER, G. P., AND ALTER, C. M.: The Atomic Weight of Lead from Katanga Pitchblende. Jour. Am. Chem. Soc., vol. 55, pp. 2785–2792, 1933.

——: The Atomic Weights of Several Radiogenic Leads. Idem, vol. 57, pp. 467–471, 1935.

BAXTER, G. P., AND BLISS, A. D.: The Atomic Weight of Uranium Lead from Swedish Kolm. Idem, vol. 52, pp. 4848–4851, 1930.

BAXTER, G. P., FAULL, JR., J. H., AND TUEMMLER, F. D.: The Atomic Weights of Some Radiogenic Leads. Idem, pp. 702–705, 1937.

BAXTER, G. P., AND GROVER, F. L.: A Revision of the Atomic Weight of Lead. Idem, vol. 37, pp. 1027–1061, 1915.

BAXTER, G. P., HÖNIGSCHMID, O., AND LEBEAU, P.: Seventh Report of the Committee on Atomic Weights of the International Union of Chemistry. Idem, vol. 59, pp. 219–226, 1937.

CLARKE, F. W., AND STEIGER, G.: The Relative Abundance of Several Metallic Elements. Jour. Wash. Acad. Sci., vol. 4, p. 58, 1914.

CROOK, T.: History of the Theory of Ore Deposits. Murby and Co., London, 163 pp., 1933.
GREGORY, J. W.: Ore Deposits and Distribution in Depth. Trans. Roy. Inst., p. 9, 1906.
——: Ore Deposits and Their Genesis in Relation to Geographical Distribution. Jour. Chem. Soc., Trans. 121, pp. 750–772, 1920.
——: The Elements of Economic Geology. Methuen and Co., Ltd., London, 312 pp., 1928.
HECHT, F., AND KROUPA, EDITH: Über die Atomgewicht einiger Proben von Radiogenem Blei. Zeit. anorg. allgem. Chem., vol. 226, pp. 248–256, 1936.
HEVESY, G., AND HOBBIE, R.: Lead Content of Rocks. Nature, vol. 128, pp. 1038–1039, 1931.
HOLMES, A.: Rock-lead, Ore-lead, and the Age of the Earth. Idem, vol. 117, p. 482, 1926.
——: Ore-lead and Rock-lead and the Origin of Certain Ore Deposits. Idem, vol. 124, pp. 477–478, 1929.
——: Lead Content of Rocks. Idem, vol. 128, pp. 1039–1040, 1931.
——: The Thermal History of the Earth. Jour. Wash. Acad. Sci., vol. 23, pp. 169–195, 1933.
——: The Age of the Earth. Nelson Classics, London, 263 pp., 1937.
HOLMES, A., AND PANETH, F. A.: Helium-ratios of Rocks and Minerals from the Diamond Pipes of South Africa. Proc. Roy. Soc. London, A, vol. 154, pp. 385–413, 1936.
HÖNIGSCHMID, O.: Neuere Atomgewichtsbestimmungen. Zeit. Electrochem., vol. 25, p. 91, 1919.
HÖNIGSCHMID, O., SACHTLEBEN, R., AND BAUDREXLER, H.: Über das Atomgewicht des Uranbleis. Zeit. anorg. allgem. Chem., vol. 214, pp. 104–110, 1933.
JEFFREYS, H.: On the Radioactivities of Rocks. Gerlands Beiträge z. Geophysik, vol. 47, pp. 149–170, 1936.
MARBLE, J. P.: The Atomic Weight of Uranium Lead from Great Bear Lake, N. W. T., Canada, Pitchblende. Jour. Am. Chem. Soc., vol. 56, pp. 854–856, 1936.
——: Atomic Weight of Lead from Galena, Great Bear Lake, N. W. T., Canada. Idem, vol. 59, pp. 653–655, 1937.
PANETH, F. A., AND KOECK, W.: Heliumuntersuchungen. X. Über eine Methode zur Messung kleinster Radiummengen. Zeit. Physik. Chem. Bodenstein-Festband, pp. 145–161, 1931.
PIGGOT, C. S.: Isotopes of Uranium, Thorium and Lead, and Their Geophysical Significance. Phys. Rev., vol. 43, pp. 51–59, 1933.
PIUTTI, A., AND MIGLIACCI, D.: Sul peso di combinazione del piombo di una cotunnite vesuviana. Rend. Att. R. Accad. Naz. Lincei, Ser 5, vol. 32 (2° Sem.), pp. 468–472, 1923; and Gazz. chem. ital., vol. 54, pp. 605–610, 1924.
RICHARDS, T. W., KING, H. S., AND HALL, L. P.: Attempts to Fractionate Mixed Isotopes of Lead and the Atomic Weight of This Metal. Jour. Am. Chem. Soc., vol. 48, pp. 1530–1543, 1926.
URRY, W. D.: The Occurrence of Radium, Uranium and Potassium in the Earth. Proc. Am. Acad. Arts and Sci., vol. 68, pp. 137–144, 1933.
WRIGHT, J. F.: Geology and Mineral Deposits of a Part of Southeastern Manitoba. Canada Geol. Surv., Mem. 169, 150 pp., 1932.

THE WISCONSIN LEAD–ZINC DISTRICT. PRELIMINARY PAPER.

CHAS. H. BEHRE, JR., E. R. SCOTT, AND A. F. BANFIELD.

ABSTRACT.

This paper summarizes intermittent study through a six year period, using methods not hitherto applied to the district. The results have shown that the ores are richer in pyrite than formerly recognized, and probably also in wurtzite (now almost wholly converted to sphalerite). In zinc sulphide deposition rhythmic banding is common. It and the iron sulphide are both colloform. The ore minerals generally show crustification and the paragenetic order is simple. The presence of peripheral pyrite in many veins, as opposed to central marcasite, suggests acid solutions neutralized by contact with the wall rock.

Structurally the ores are chiefly near the flanks of basins. Brittle dolomites are the most favored host rocks and the ores are clearly for the most part fracture fillings. Mineralized faults of small displacement are common and pass through the otherwise relatively impervious "oil rock," at least in some cases. The faults and folds are both believed to be the result of tectonic movements.

When assembled as a whole, these field and laboratory data favor but do not conclusively prove that the ores are due to rising solutions, probably of ultimate magmatic origin; this concept supports other recent studies of a chemical and mineralogical sort.

INTRODUCTION.

THERE would be no progress in the study of ore deposits if our technique remained always the same. Improvements in technique are synonymous with a better understanding of ore deposition. It is desirable, however, not only to improve technique, but also to apply the new methods to older problems to see what new light may be shed. It is this consideration that seemed to justify the restudy of so well-known a region as the lead and zinc district of the upper Mississippi Valley; the reexamination of this locality worked over by many leading geologists might otherwise appear presumptuous.

Such a study is a labor of patience. The geologist familiar with the western bonanza camps, in which now only a relatively small part of the workings is still accessible, must be prepared for an even more restricted view, for here the district has been largely abandoned. Although up to the year 1905 the value of zinc produced in Wisconsin, Iowa, and northern Illinois totalled $10,000,000 and that of lead $50,000,000, the production has now declined until that of Illinois and Iowa is today zero; in 1935 Wisconsin alone maintained a production, yielding 398 short tons of lead concentrate, valued at $16,963 and 33,027 tons of zinc concentrate valued at $379,262. From 1906 to 1935 inclusive the district produced 778,952 short tons of metallic zinc and 83,888 tons of metallic lead.[1]

Despite this decline for the district as a whole, the Vinegar Hill Zinc Company in Wisconsin has continued steadily active and successful. Generally one or two mines are in operation at a time and the geologist must collect the data, then await the opening of another mine. Once abandoned, a mine becomes inaccessible, being flooded in a relatively short time. In the course of six years of field work, therefore, only eight mines could be examined.

Aid has been furnished by colleagues, especially Doctors John R. Ball, J. T. Stark, W. E. Powers, and A. L. Howland. Students at Northwestern University have borne noteworthy shares of the work, particularly Messrs. A. F. Banfield, E. R. Scott, and I. T. Schwade. Special thanks are due the management of the Vinegar Hill Zinc Co., notably Mr. W. N. Smith, General Manager, and Mr. O. E. DeWitt, Geologist, for repeated favors and invaluable data; this cooperation was most generous. The writer is also indebted for suggestions to Mr. G. M. Fowler, Prof. E. S. Bastin, and especially to his former colleague and teacher, Prof. U. S. Grant.

It seems unnecessary to attempt a review of all previous work on this well-known district. What follows is mainly new data, but brief reference to earlier studies will be made from time to

[1] U. S. Bur. Mines, Minerals Yearbook, 1936.

time. Any restudy of a region so long scrutinized must necessarily be based in part upon the work of earlier investigators, and mention should here be made especially of the pioneer work of Chamberlin,[2] of certain excellent detailed studies by Grant,[3] Bain,[4] and Cox,[5] and of the recent stimulating summaries by Spurr[6] and Emmons.[7]

The chief problems of the district are structural and mineralogic. These will be taken up in turn. Perhaps the most significant characteristic of the district is its simplicity. Although not easy to interpret, at least the facts of ore occurrence and composition are less complicated than usual. Even in comparison with those other districts of the type to which Americans have applied the term "Mississippi Valley," it is simple. As such it merits special study, partly for itself alone, and partly for the light which it may shed upon other districts of that widespread and important type.

The three authors have shared in compiling the data given below. For many of the conclusions about structural features Scott is largely responsible; for many of those about mineralogy and paragenesis, Banfield. Most of the general conclusions respecting the bearing of these facts upon ore genesis are those of Behre.

GENERAL SETTING.

Location.—The Wisconsin lead-zinc district covers parts of three counties—Grant, Iowa, and Lafayette, in the southwestern part of the state. Today mining is confined to the area between

[2] Chamberlin, T. C.: The ore deposits of southwestern Wisconsin. Wis. Geol. Surv., Geol. of Wis., vol. 4, pp. 365–571, 1882.

[3] Grant, U. S.: Lead and zinc deposits of Wisconsin. Wis. Geol. Surv. Bull. 14, pp. 100, 1906.

[4] Bain, H. F.: Zinc and lead deposits of the Upper Mississippi Valley. U. S. Geol. Surv. Bull. 294, pp. 155, 1906.

[5] Cox, G. H.: Lead and zinc deposits of northwestern Illinois. Ill. Geol. Surv. Bull. 21, pp. 120, 1914.

[6] Spurr, J. E.: Upper Mississippi lead and zinc ores. Eng. Min. Jour., vol. 117, pp. 246–292, 1924.

[7] Emmons, W. H.: The origin of the deposits of sulphide ores of the Mississippi Valley. Econ. Geol., vol. 24, pp. 256–266, 1929.

Hazel Green, Shullsburg, and Platteville, but in the past it was worked over a far greater area, extending northward to Dodgeville, Wisconsin, southward to Elizabeth, Illinois, and westward as far as Dubuque, Iowa.

Stratigraphy.—The formations in which the ores are found chiefly are of Ordovician and Silurian age. The most recent and most detailed work on the rocks that bear most of the ores in the mining region has been carried on by Kay,[8] and by Bays and Raasch.[9] In view of the unsettled questions still existing in the studies referred to, no attempt is here made to follow detailed stratigraphic subdivisions, but a practical stratigraphic column is given in Fig. 1 and the units there recognized will be referred to below. The "Decorah," as used in the figure includes the lowest part of the Galena formation of most authors; by others the term "Decorah" embraces also the uppermost subdivision of the underlying Platteville. As here used, it consists of some fifteen feet of "oil rock" and limestone and fifteen feet of overlying shale and limestone; these members are designated by Kay the Guttenberg and Ion respectively.

Drillers and mine operators confine the term "oil rock" to the lowest two feet or so of the Guttenberg; these consist of dark brown shale interstratified with beds of lenticular or nodular limestone, passing upward almost gradationally into a purer but still brownish limestone; the "oil rock" is bottomed by an unconformity, a phosphate horizon and a dwarf fauna.[10] In outcrops the oily appearance of the lowest two feet is not well marked; in fact, the beds gradually weather back so as to be inconspicuous. When fresh, as where seen underground, the rock is strongly oily and yields the following gases on heating: heavy hydrocarbons 15.11 per cent., methane 35.98 per cent., H_2S 6.79 per cent., CO_2 18.12 per cent., CO 8.40 per cent., and O, H, and

[8] Kay, G. M.: Stratigraphy of the Decorah formation. Jour. Geol., vol. 37, pp. 639–671, 1929. Kay, G. M.: Ordovician system in the Upper Mississippi Valley. Ks. Geol. Soc., 9th Ann. Field Conf. Guidebook, pp. 281–295, 1935. Kay, G. M.: Ordovician Stewartville-Dubuque problems. Jour. Geol., vol. 43, pp. 561–590, 1935.

[9] Bays, C. A., and Raasch, G. O.: Mohawkian relations in Wisconsin. Ks. Geol. Soc., 9th Ann. Field Conf. Guidebook, pp. 296–301, 1935.

[10] Ball, J. R., Oral communication, 1936.

N 15.65 per cent.[11] It is to the reducing action of this rock that ore deposition has been ascribed by some investigators;[12] others have attributed to the "oil rock" the compaction (through rearrangement and loss of volatile constituents) that yielded sub-

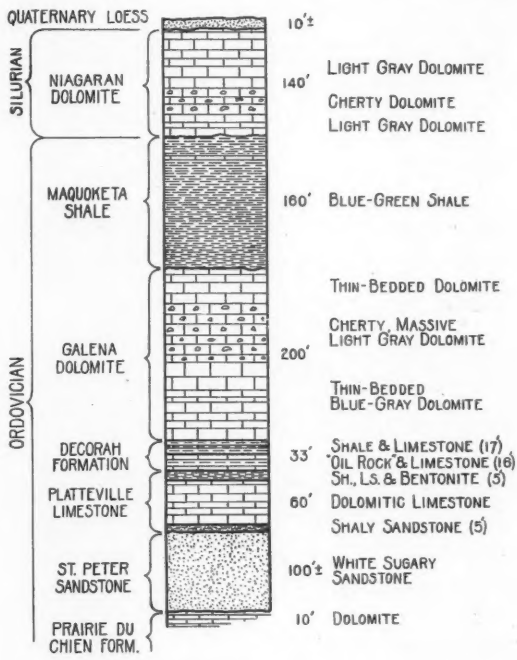


FIG. 1. Generalized columar section, to scale, of the Paleozoic rocks in the Wisconsin lead-zinc district.

sidence and fracturing of the overlying beds.[13] In exploring for ore from the surface, drilling is generally stopped in the "oil

[11] Shaw, E. W., and Trowbridge, A. C.: Galena-Elizabeth folio, Ill.-Iowa. U. S. Geol. Surv. Geol. Atlas of U. S., Folio no. 200, p. 4, 1916.

[12] For example: Grant, U. S.: *Op. cit.*, pp. 78–79; Bain, H. F.: *Op. cit.*, p. 135.

[13] See for illustration: Bain, H. F.: *Op. cit.*, pp. 70, 135–136.

rock" if no ore has been found, and this despite the fact that in the northerly part of the district most of the ore has come from below the "oil rock."

STRUCTURE AND ITS BEARING ON MINERALIZATION.

General Structure.—Regionally the structure is the westerly side of the Wisconsin arch, which is floored at depth by the pre-Cambrian. This arch has been well outlined with structure contours by the geologists of the Wisconsin, Illinois, and Iowa geological surveys. The axis of the arch trends generally southward. Its eastern flank dips more steeply than its western one, the dips amounting to 30–40 feet per mile on the east and 10–25 feet per mile on the west. In the ore region the strikes are generally west-northwesterly but near Galena, Illinois they are somewhat north of east.

The Basins.—The detailed structure consists of a series of elliptical basins, ranging from one to five miles in maximum dimensions and having a ratio of length to breadth which varies from 10 : 1 to 1 : 1; the dimensions and ratios indicated are measured with respect to the outermost closed contour. The axes of the elongated basins trend parallel to the regional strike. The basins have been contoured with an accuracy probably exceeding that of any other ore district in the world, and such detailed mapping was carried on as early as 1905, when structure contouring even of oil fields was not yet a common practice.

Between the synclines are corresponding anticlinal structures of the same general dimensions and type. They may be compared, as Bain [14] pointed out, with the canoe-shaped structures in the Appalachians. There is one striking contrast with the latter, however, in the fact that in Wisconsin the highest and lowest points are generally opposite each other, instead of being staggered as in the Appalachians; the condition in Wisconsin suggests either (1) different degrees of compression in different parts of the area or (2) differences in the initial elevation of the basement complex and in the thickness of the overlying beds.

[14] *Op. cit.*, pp. 41–43.

It is also noteworthy that the basins are in general better marked than the intervening elevations. Geometrically they appear as pronounced downfolds superimposed on an otherwise somewhat undulatory pattern. This impression is not readily gained from a small number of basins but is sufficiently noticeable to be recorded by at least one geologist.[15]

In a few localities unusually steep dips occur, generally in association with well-marked folds. One such fold follows the boundary line between Lafayette and Iowa counties. Another extends from Redrock, Lafayette County, Wisconsin, westward toward Cuba. At Meekers Grove the north limb of an anticline dips so steeply as to decline 90 feet in about an eighth of a mile, a strikingly steep dip to which reference will be made again below.

It has been suggested by Emmons[16] that the ore deposits lie along a northwestward continuation of the crest of the LaSalle anticline. This concept is tempting because of its obvious bearing on deriving the solutions from shallow igneous masses. To the writer, however, it appears scarcely justifiable. Careful mapping by J. V. Howell, F. T. Thwaites, A. C. Trowbridge, L. E. Workman, and Marvin Weller show in the subjacent Cambrian and Ordovician formations a northward dying out of that structure and its essential confluence with the southwesterly slope of the Wisconsin arch; this is perhaps best seen in the excellent structure maps of the Kansas Geological Society's Ninth Annual Field Conference.[17]

Most of what is given above is not at all new. It simply reflects the viewpoint of the writers. In beginning this work, however, it was thought that improved technique developed in the last twenty-five years might discover new facts. Mines were therefore mapped in the detail customarily used in western mining districts. Most of the data here presented were obtained in two mines, the Crawford near Hazel Green, Wisconsin, and the Doyle-Harty near Shullsburg.

Further Data and the Origin of the Basins.—It appeared de-

[15] Bain, H. F.: *Op. cit.*, p. 35.
[16] Emmons, W. H.: *Op. cit.*, p. 257.
[17] *Op. cit.*, pp. 354–360, 1935.

sirable first to eliminate as nearly as possible the personal equation in observations. An area which had been carefully mapped by Grant and his colleagues was remapped with the plane table, to see whether the structural data available today might represent sufficiently objective facts, so that in general confidence could be placed in the earlier geology. The area mapped lay west of the town of Platteville and covered a strip of three by two miles, the longer dimension being in a north-south direction.[18] The new map shows a minor flexure not found by Grant and his associates, but the trends, dips, and dimensions of the folds are closely similar and the slight differences are readily assigned to personal factors or lie within the range of normal observational errors.

Extensive exploratory drilling has been carried on by various mining companies. Such work by the Vinegar Hill Zinc Company has been outstanding in its detail, close spacing, accuracy, and systematic recording. The company kindly placed this material at the disposal of Behre and of Scott and his assistant Mr. I. T. Schwade. The drilling is carried on with a churn drill. The shattered material is bailed up at intervals of five feet or less. The positions and altitudes of the holes are carefully surveyed with a transit. In the neighborhood of Hazel Green and Shullsburg, Wis., the region where such exploration is now in progress, the ore is chiefly confined to the strata above the "oil rock." Hence drilling is discontinued when the drill enters the "oil rock." For each hole two facts are entered on the map: (1) the altitude of the collar of the hole and (2) the altitude at the top of the "oil rock." From these data it should be possible to draw accurate structure contour maps upon the top of the "oil rock" and thus outline the basins.

Two questions must be faced, however, if the resulting structure contour map is to be regarded as bearing significantly on ore deposition. One of these is whether the structures thus outlined are fallacious; is the horizon called "oil rock" reasonably constant or does it represent a sedimentary facies of variable strati-

[18] Scott, E. R.: The structural control of ore deposition in the Upper Mississippi Valley lead-zinc district. Northwestern Univ. Master's Thesis, Unpublished, 1934, pp. 23–24, and Fig. 3.

graphic depth? The other is, granted that the structures are real, are they merely subsidence features or are they tectonic?

With respect to the first question, the structures drawn on the basis of surface outcrops are identical in nature with those drawn on the basis of drill records; the dimensions, directions of axial trends and dips are too nearly similar for coincidence alone. Thus it appears that the method of structure mapping from drill records is satisfactory.

As to the second question, the reply is not definite. It has been stated by most earlier investigators that the "oil rock" is thickest under the basins.[19] The truth of this statement may well be questioned. There is evidence demonstrating that in most of the non-mineralized region the "oil rock" is lacking,[20] but none to show clearly that it thickens only in the fold troughs. Indeed, Cox was of the opinion that the "oil rock" thickened not only in the troughs but *at the crests of the folds as well,* and inferred that this condition might result from the typical behavior of a thin, incompetent bed of shale between hard, competent layers of limestone.

In some of the mines, the writers have observed small basin-like depressions, three feet or less in depth and ten to seventy feet in width; these seem to represent fillings of Decorah shaly limestone developed in valleys (or folds) in the underlying uppermost shaly Platteville, which is generally also slightly deformed. Limestone and not shale occupies these basins, and the overlying beds are continuous and show no deformation across the top of the depression (Fig. 2). The very horizontality of the beds lying within small basins of this sort argues against noteworthy compaction in similar larger ones. These facts seem to point to an explanation for the basins other than mere subsidence. Indeed, Grant has shown that some of the stronger folds are reflected in the underlying St. Peter and Prairie du Chien;[21] the axes of such folds are again parallel to those of the lesser basins.

[19] Bain, H. F.: *Op. cit.*, p. 39.

[20] Cox, G. H.: Lead and zinc deposits of Northwestern Illinois. Ill. Geol. Surv. Bull. 21, p. 26, 1914.

[21] Grant, U. S.: *Op. cit.*, p. 53.

It thus seems logical to consider the alternative explanation —the origin of the basins by tectonic forces. The localization of the folds may well be determined by irregularities in the topography of the underlying rocks—most probably of the pre-Cambrian. Such forces should operate essentially at right angles to the fold axes, and these in turn should be parallel to the regional strike, as in fact they generally are. Where the compression became fairly intense it might well be expected to break the beds, and faults might be looked for.

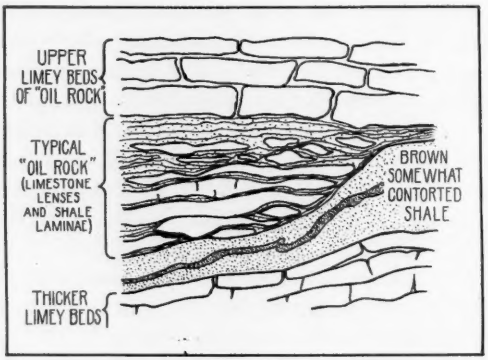

UPPER LIMEY BEDS OF "OIL ROCK"
TYPICAL "OIL ROCK" (LIMESTONE LENSES AND SHALE LAMINAE)
THICKER LIMEY BEDS
BROWN SOMEWHAT CONTORTED SHALE

FIG. 2. Sketch of small basin of deposition of Guttenberg "oil rock," Crawford Mine. Width of exposure, five feet.

General Relation of Ore to Structural Features.—For the ensuing discussion the reader should have in mind the general modes of ore occurrence. Briefly, the ore occurs in five ways: (1) disseminated in the "oil rock" of the Guttenberg and in the underlying shales of the uppermost Platteville formation ("Spechts Ferry" member); this is not an important mode of occurrence; (2) in vertical joint-like cracks or crevices; (3) in inclining fractures ("pitches"); (4) in masses of various forms as cement between irregular breccia blocks near or in any fractured zone; and (5) parallel to but between the beds, in the so-called "flats." All of these ways of occurrence except (1) are clearly fillings of

pre-existing openings. Replacements of appreciable volume are negligible.

Localization of the Ore in the Basins.—One of the most striking features of the afore-mentioned types of ore occurrence is the localization in or near the basins. Recognized since almost the first mining operations, the idea was first clearly expounded with supporting data by Bain and Grant.

In detail, however, the fissures that carry the ore are typically not well developed in the basin but on its flanks. The deepest part of the basin is generally but slightly mineralized, whereas the typical larger ore bodies are hollow in the central part, rather like elongated doughnuts, the hollow coinciding with the deepest part of the trough. They thus strongly suggest the "circles" of the Joplin district.[22] This is well shown by a series of contoured structures compiled by the writers from data made available by the kindness of the Vinegar Hill Zinc Company (Fig. 3).

In some instances quoted by Cox [23] the main ore body is on or near the anticlinal crest, but this is to be regarded as exceptional, as can be shown by a rough statistical analysis.

Fissures, Faults, and Ore Deposition.—Much has been said in the past respecting the absence of faults in the district. Although it has been recognized that important bodies of ore, especially where rich in lead, occurred in fissures (the "crevices," "openings," "ranges," "two-o'clock," "ten-o'clocks" and the like), these were pictured as joints, more or less enlarged by solution. Such bodies are especially prominent in the Iowa lead-zinc district, near Dubuque. Somewhat similar structurally (though not, of course, in the nature of the filling) are sandstone "dikes" occurring in the district, one of which was observed in the Trewartha mine.

One of the striking things generally noted is the parallelism of these fractures with the axes of the basins. Thus, Grant [24] figures both a mine map of a crevice deposit, and a map of a larger

[22] Smith, W. S. T., and Siebenthal, C. E.: Joplin district folio. U. S. Geol. Surv. Geol. Atlas no. 148, pp. 15–16, 1907.

[23] *Op. cit.*, p. 47.

[24] Grant, U. S.: *Op. cit.*, pp. 66, 68.

area; in both the crevices trend easterly, approximately parallel with the fold axes. Bain shows several excellent illustrations of such parallelism.[25]

In our studies crevices were repeatedly recognized. They are joints, commonly widened by solution and in such instances bearing noteworthy quantities of ore.

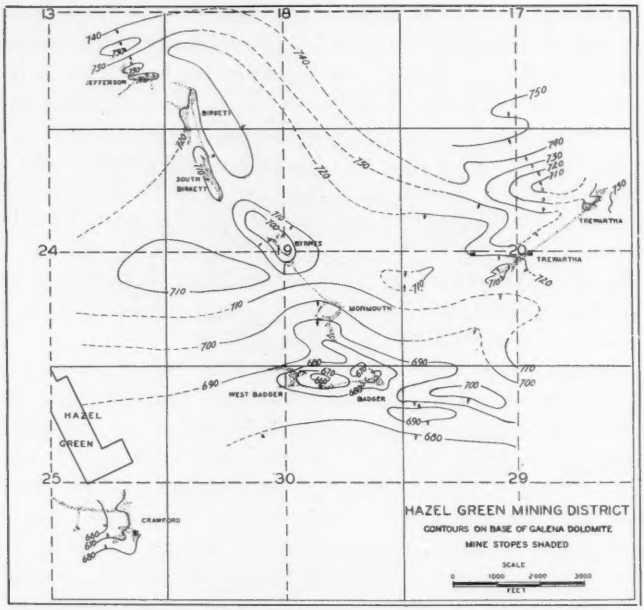


FIG. 3. Contour map of area east of Hazel Green, Wis.; largely after Scott, from data furnished by the Vinegar Hill Zinc Company. Outlines of areas mined out are shaded. Note that much of the ore forms elliptical masses *surrounding* the centers of basins.

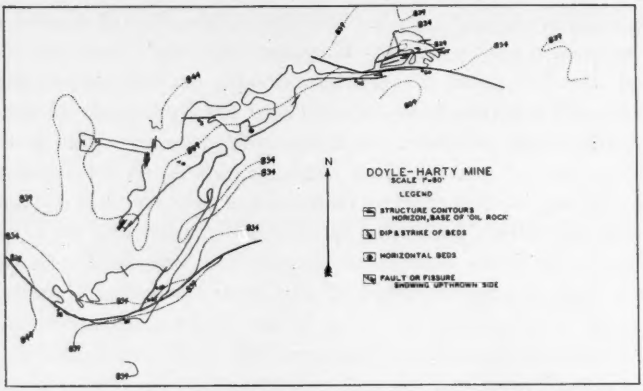
On the other hand, most of the vertical or steeply inclined fissures having noteworthy vertical continuity show traces of movement. No large faults have been found, mainly, it is believed,

[25] *Op. cit.*, Plate VIII (Opp. p. 58), and Plate X (Opp. p. 82).

because no stratigraphic horizons are sufficiently well marked to recognize a definite offset. Were the "oil rock" commonly offset, the effect would of course be noticeable, but mining operations have not generally been carried below the "oil rock" in those localities now accessible. It is noteworthy, however, that in the mines located where drilling has been used by us for structure contouring, several cases of faults of five to fifteen feet displacement are definitely recorded by structure contours and are correlated with faults observed underground. Two such instances are furnished by the maps of the Doyle-Harty and Crawford mines (Figs. 4 and 5). Most of the faults noted are reverse faults of moderate dips. These generally show considerable shattering and some drag on one or both walls. No case is known where faults of this type are seen to die out upward or downward, but, as in the more northerly of the faults in the southwest workings of the Doyle-Harty mine, they may flatten until parallel with the bedding. In such cases the fault passes into the zig-zag type described below.

Faults of the type described are always mineralized. Those which are clearly reverse faults dip toward the center of the trough in which the ore is found; those which are normal dip away from the axis. The effect in either case is thus to compress the "keystone" in the arch of the trough, although in the case of the normal faulting there must be crinkling and shattering of the keystone to permit such compression (Fig. 6). Such faults predominantly strike parallel to the fold axes, but also cut across the axes at the ends of the structures, as is well shown in the workings west of the shaft of the Crawford Mine.

Many of the faults are clearly of the "zig-zag" type (Fig. 7); that is, in vertical section they are parallel to the bedding for some distance, then cut across it a way. As a rule, the flatter parts of the faults follow shaly layers or at least pronounced partings parallel to the bedding planes. The direction in which the major component of movement trends will determine whether the more steep or the more gentle arm of such a zig-zag is to be



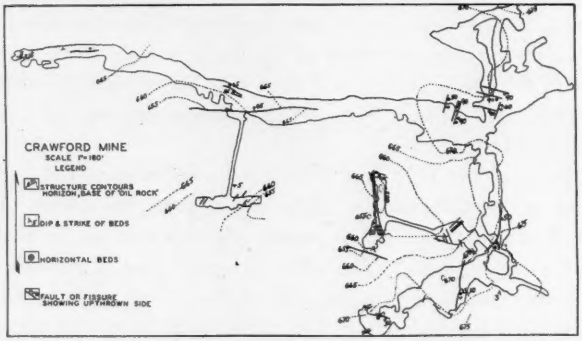


FIG. 4 (above). Geologic map of the Doyle-Harty mine, Shullsburg, Wis. Structure contours (dashed lines) from drill records furnished by Vinegar Hill Zinc Company. Fault traces and other underground data based on mapping by Behre.

FIG. 5 (below). Geologic map of the Crawford Mine, near Hazel Green, Wis. Data from same sources as Fig. 4.

the wider part of the vein;[26] if, as is usually the case, the movement is chiefly compressional and upward, it would be expected

[26] Behre, C. H. Jr.: Bedding plane faults and their economic importance. Amer. Inst. Min. Met. Eng., Tech. Public. no. 767, pp. 14–16, 1937. Emmons, W. H.: Principles of economic geology, p. 185 and Fig. 82. McGraw-Hill Book Co., New York City, 1918.

that the wider part would be the horizontal one. The predominance of flat bodies of ore (the "flats" of miners) suggests that compression is dominant.

The third type of fault is unique in the experience of the writer. It is a modified zig-zag type, certain components of which are parallel to the beds. Mineralized similarly to those already described, it clearly antedated ore deposition. Illustrations are

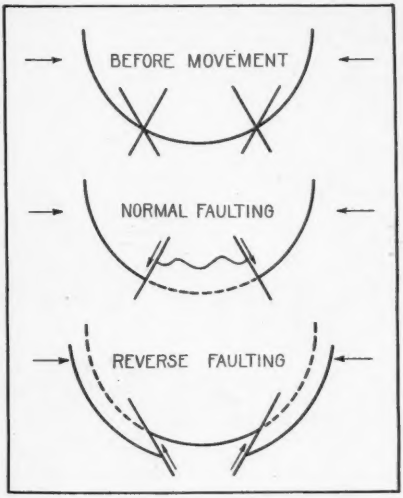


FIG. 6. Diagram of "keystone" fault pattern, normal and reverse, as found in Wisconsin zinc mines. The effect when the faults are normal is not compressional except that it gives room for upward expansion; in that case some crumpling is needed in the "horst" block.

furnished by Figs. 9 and 10. In both cases a block lies obliquely between two bordering lesser faults. It is possible to correlate the higher beds in the relatively downdropped block with higher beds in strata normally appearing just below the roof on both sides of that block. There is evidence of crumpling in the strata adjacent to both ends of the block. Although the details are not clear, the impression is gained that two shear planes bordering

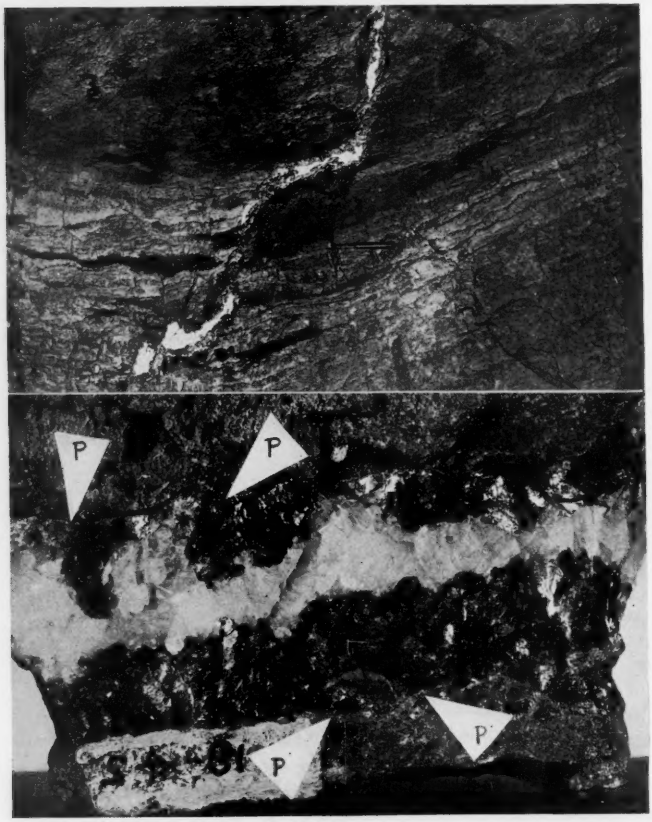


FIG. 7 (above). Photograph of fault-fissure vein, south workings, Crawford mine. View northwest along strike of fissure. Height of exposure about seven feet. Shows alternate flattening and steepening of fault. Note that fissure and mineralization were widest where fissure was horizontal, that is, movement on left (southwest side) was chiefly upward.

FIG. 8 (below). Section of typical vein, showing thin bordering film of pyrite (P), sphalerite (wurtzite), and central calcite. Width of vein, two inches. Badger Mine, near Hazel Green, Wis.

the block have broken obliquely across it and that the block has suffered compression from both ends, and has been shattered and rotated into a reduced space, room being made by upward and

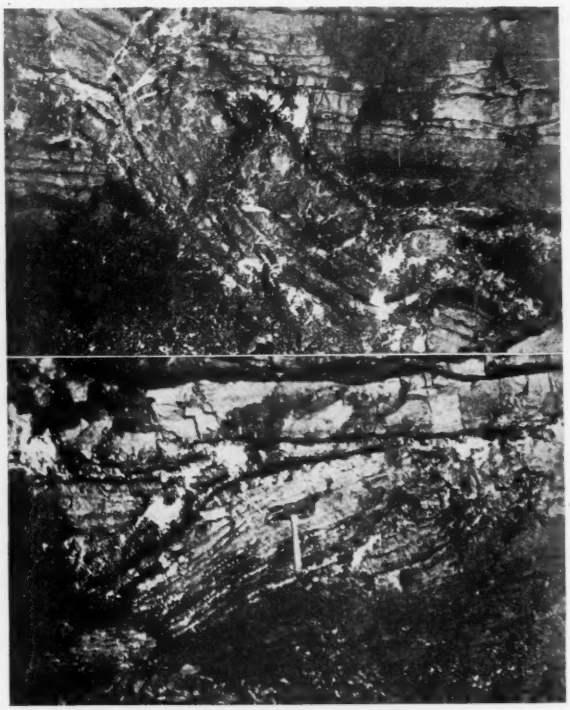


FIG. 9 (above). Bedding plane fault in "Mule Barn stope," Crawford mine. Exposure approximately eight feet wide.

FIG. 10 (below). Bedding plane fault, southeastern heading, Crawford mine. Exposure approximately six feet wide.

(or) downward bulging, and displacement of the beds above and below. The evidence of shortening cannot be denied. There is no sign of extensive solution and the fact that the ends of the

displaced block are closely mashed against the country rock clearly shows that neither tension nor collapse after solution has been the cause of deformation. Above and below, after obliquely crossing the shattered stratum, the two bordering fault planes have flattened, merged and, following along the bedding, have once more become inconspicuous.

Faults of this kind are fairly common and one or more examples have now been found in every mine carefully examined. They are characteristic and point to much more tangential stress than has generally been assumed for the district. They are not readily noted, however, and it is small wonder that they, like the other faults mentioned, have been generally overlooked.

These features that locally cross the "oil rock," are believed to dispose of the argument that mineralizing solutions might have travelled only *downward* because fractures extend only *down to* the "oil rock." Once the tectonic nature of the basins and fractures and the ubiquity of the faults is recognized, the district loses much its structural uniqueness, and its ore channels begin to approximate those seen in other, generally more highly mineralized and extensively shattered districts.

The close linkage between mineralization and faulting is most striking. For a long time much of the work in the extreme northwest heading of the Crawford mine was carried on with a steam shovel and the roof under which the machine operated was a thrust fault plane striking about N. 80° W. and dipping 50° N.; the beds showed typical drag and the "oil rock" in the hanging wall was lifted approximately five feet. Similar relations obtained in the southwestern heading of the Doyle-Harty mine toward the end of November 1936, for all the work was being conducted under a well-marked thrust fault which, with a curved strike averaging N. 85° W., dipped about 60° S.W. This fault showed a well-developed clayey gouge and was iron stained and highly mineralized. Though the displacement as seen underground could at best be roughly estimated at from five to fifteen feet, it was clearly demonstrable by structure contours based on fairly closely spaced drill holes. Both of these features were

dubbed "pitches" by the miners. They represent two better-than-average but by no means exceptional illustrations of faulting. It may be significant, as bearing upon the direction of solution movement, that in both instances the greater part of the mineralization lay *beneath* the gouge-filled fault plane.

MINERALIZATION, FACT AND THEORY.

Sources of Data.—As already stated, almost all of the mines of the district are now shut down. There was far greater activity in the first decade of this century and great confidence may be placed in the careful observations of Bain, Cox, and Grant, especially so in view of the far larger amount of workings then available. The present writers, on the other hand, have been able to study only eight mines—the Blockhouse mine near Platteville, the James, Mullen, and Doyle-Harty near Shullsburg, the Badger, Crawford, and Trewartha near Hazel Green, and the McKinley, near Dodgeville. Of these the mineralogy in four (Doyle-Harty, Crawford, Badger, and Trewartha) has been studied in considerable detail, with the help of polished sections. A very brief summary of this work has already been published.[27] Detailed discussions of the polished section studies are to be presented in a later paper.

Primary Minerals.—One of the attractive features of these ores, because it seems to favor a more nearly perfect understanding of the chemistry of deposition, is their simple mineralogy. The minerals reported include only the following:

Primary Minerals.

Barite	Marcasite
Calcite	Pyrite
Chalcopyrite	Quartz
Galena	Sphalerite
Gypsum	Wurtzite

An arsenic-bearing mineral, inferred from chemical analysis. sis.

[27] Banfield, A. F.: The micrography of the lead and zinc ores of the Upper Mississippi Valley. Ill. Acad. Sci. Trans., vol. 26, p. 98, 1934.

Secondary Minerals.

Anglesite	"Limonite"
Azurite	Malachite
Calamine	Melanterite (and related forms)
Cerussite	Pyrolusite (and related forms)
Hydrozincite	Smithsonite

Sulphur

In this list no attempt has been made to include the minerals found in some of the deposits of near-by regions that do not correspond in type to the lead-zinc ores here discussed, nor will the oxidation products of the primary minerals listed receive further attention in this paper.

Dolomitization and Chertification.—In other similar ore districts of the Mississippi Valley, the presence of dolomite and chert has been assigned by authors to the same process (though possibly to a differing time) whereby the ores were deposited. Although there is a suggestion that studies may ultimately extend that explanation to the region here considered, the evidence is as yet wholly inconclusive and the subject therefore is not faced in this preliminary paper.

Description of Conspicuous Minerals.—The calcite appears to occur in two forms. In one the elongated scalenohedral crystals of "dog-tooth spar" type are especially conspicuous. In the Eagle Point Quarry at Dubuque, Iowa, such forms may show zoned marcasite inclusions. In the other, the unit rhombohedra form the larger faces and are modified by polar edges (v and w, Dana) the effect being to yield short, stubby crystals. The "dog-tooth" type invariably occurs in late vugs; the rhombohedral form is commonly coated with other sulphides or may itself coat them, and thus is in part earlier, perhaps in part contemporaneous with the other kind of calcite.[28]

The galena rarely shows unusual features. Well-formed cubes are common. In rare cases these exhibit curved surfaces or

[28] See, for another example, Loughlin, G. F., and Behre, C. H., Jr.: Zoning of ore deposits in and adjoining the Leadville district, Colorado. ECON. GEOL., vol. 29, p. 252, 1934.

dihedral angles, indicating slight distortions, or even (but rarely) elongated curved blades, which point to extensive deformation. The galena occurs most conspicuously in deposits above the level of most of the sphalerite, strongly suggesting "zoning."

Quartz is rare in the ore bodies, occurring only in small vugs.

Marcasite and pyrite show interesting relations. The former is by far the more common. Some iron sulphide occurring in openings as nodular masses with radial crystals was hitherto regarded as marcasite but is now known to be pyrite,[29] and it seems probable that pyrite is far more widespread than has generally been recognized. The spherical arrangement of the masses suggests that they were marcasite colloidally precipitated in typical

FIG. 11. Globular masses of colloform marcasite, Doyle-Harty mine.

nodules, and have subsequently been altered to pyrite—a reasonable assumption in view of the stability relationships of the two minerals. A second place in which pyrite appears is at the margins of the fissures, almost every one of these having its pyritic coating, however thin (Fig. 8). It should be emphasized also, that botryoidal masses of marcasite, similar to those of pyrite mentioned above and occurring in successive shells that coat the walls of open fissures, readily break apart parallel to the shells as well as along the prismatic surfaces of the crystals in the "spherulites"; this general structure also strongly suggests colloidal deposition (Fig. 11). In the shaly beds irregular penetra-

[29] Banfield, A. F.: *Op. cit.*, p. 98. Born, Kendall: Fibrous pyrite from the lead-zinc district of Illinois. Am. Mineralogist, vol. 19, pp. 385–388, 1934.

tion, chiefly, of pyrite (?), is observed, but crystal forms are poorly exhibited and crystal individuals seldom attain 0.05 inch in width.

Wurtzite and sphalerite bear to each other much the same relations as just described for marcasite and pyrite, except that they are even more intimately intergrown. A cross-section across a mass of zinc sulphide generally shows marked elongation of the individual crystals in one direction. Under the microscope, as also to a lesser degree in the hand specimen, these blades are crossed by rhythmic bands, due in different cases to (1) changes in color from light to dark brown, or (2) the presence of pores, which appear in bands, or (3) the presence of tiny marcasite-pyrite individuals, or any of these three features together. Short, stubby, typically isometric crystals of sphalerite are in fact seen only (1) in the shales, where they crowd the laminæ apart like crystalloblastic individuals in a metamorphosed rock, and (2) on the inward surfaces of vugs or of incompletely filled veins. Globular masses of zinc crystals are common (Fig. 12). The elongated crystals of zinc sulphide are strongly suggestive of wurtzite but they are generally isotropic both under the reflecting microscope and by transmitted light. Only rarely do one or two relatively isolated individuals show birefringence and extinction. X-ray diffraction patterns, kindly made for the authors by Professor Paul F. Kerr of Columbia University, exhibit an isometric pattern; this is tentatively attributed by Professor Kerr, however, to inversion from wurtzite into sphalerite upon grinding. Attention is directed to similar relationships found by Ehrenberg [30] in certain European sphalerites. In fact the similarity in appearance of this zinc sulphide to that in European districts, notably in Silesia, Aachen, and Moresnet, is striking, even to the rhythmic bands of iron-rich sulphide that alternate with clearer bands.

A peculiar feature is the occasional finding of stalagmitic masses of ore in open cavities. These are composed of radiating sphalerite (wurtzite) and bear occasional fissures or have a small

[30] Ehrenberg, H.: Der Aufbau der Schalenblenden der Aachener Bleizinkerzlagerstaetten, etc. Neues Jahrb., vol. 64, Beil.-Bd. A, pp. 397–422, 1931.

opening passing through them now partly or wholly filled with galena or marcasite. Their form suggests the dripping of a solution from the roof upon the floor in the familiar manner of cal-

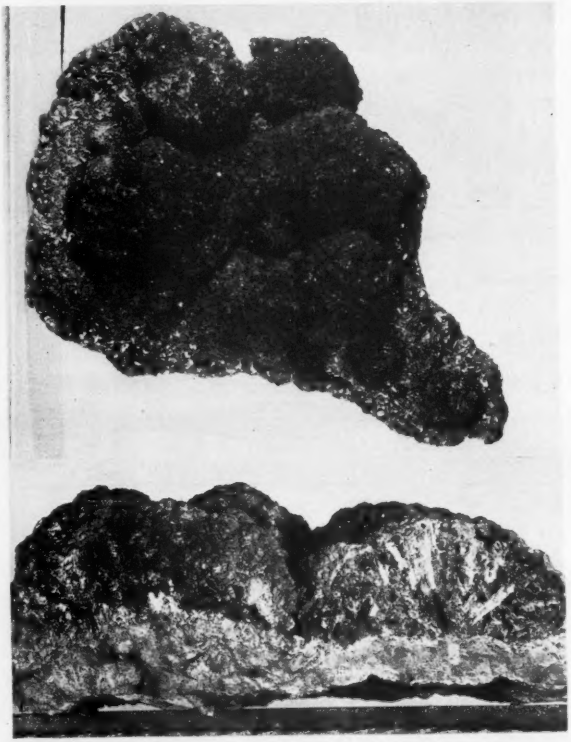


FIG. 12. Globular masses of wurtzite-like sphalerite from above and in section. Note radiating arrangement of elongated sphalerite needles.

cium carbonate deposition in caves. Such a solution might obviously be either supergene or hypogene. So far as the writers are aware, masses of this kind have been found only in the *floor* of the mines, pointing upward, a surprising fact, if true.

Paragenesis.—The paragenetic diagram (Fig. 13) expresses the evidence gleaned from careful study of about three hundred specimens. Most of the features do not merit further extended discussion. The ubiquity and long extent in time of marcasite-pyrite deposition is striking; there is, in fact, some suggestion in the higher ore bodies that a period of oxidation was followed by marcasite deposition from *descending* waters, as indicated by occasional very thin films of hydrous iron oxide between otherwise closely knit marcasite and galena; in such cases the galena, when stripped of its marcasite, is seen to be finely etched.

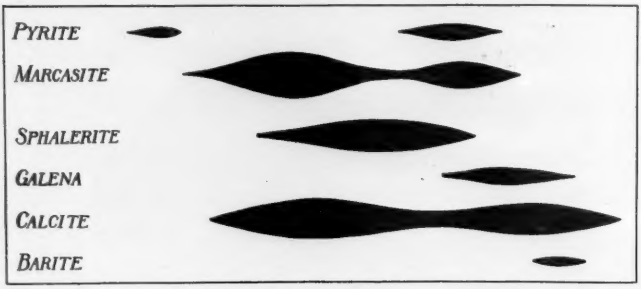


FIG. 13. Paragenetic diagram, Wisconsin-Illinois-Iowa lead-zinc district.

One more characteristic deserves comment. As already noted, the borders of veins, against the enclosing dolomitic limestone, are generally coated with pyrite; under the microscope this sends tiny stringers out into the country rock. A slight distance inward toward the vein-center the place of pyrite is generally taken by marcasite, which predominates thereafter. Although the galena almost everywhere follows the zinc sulphide, being more central in the veins, in some places the two are intermingled; in short, it is clear that there has been some overlapping in primary mineralization. Finally, after all the ore was deposited there was enough earth movement to permit shattering. Some of the ore bodies thus show particles of sulphides "floating" in masses of calcite of the dog-tooth type (Fig. 14).

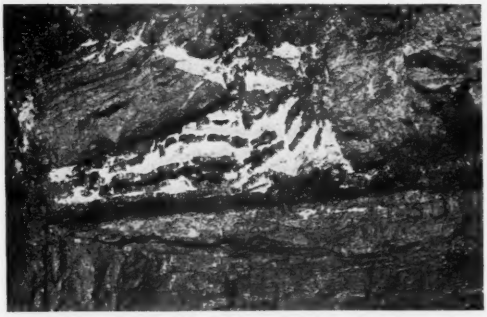


FIG. 14. Fragments of zinc sulphide ore in late calcite, Crawford mine. Width of exposure about five feet.

ORIGIN OF THE ORE.

The numerous discussions of the origin of the ore cannot be reviewed here; the senior writer can only attempt to outline his own theory, listing briefly the supporting evidence.

When all the data, new as well as old, have been examined, it appears most likely that these ores were deposited by rising solutions. The complex structural picture makes highly improbable any simple ascent in direct line, but instead the solutions are believed to have moved laterally and chiefly upward, as was made possible by the fracture pattern outlined above. The evidence is not conclusive, but favors this interpretation because:

1. Ore has been found below the "oil rock," hitherto frequently regarded as the agent that ponded the descending mineralizing solutions. The McKinley mine at Dodgeville, developed extensively in limestone twenty feet below the "oil rock," serves as an example. Indeed, ore occurs in the Maquoketa shale, in the Niagara limestone, and in the lower Platteville and Prairie du Chien. Further, the ore is not generally localized to the very bottom of each basin, as it should be if it had been ponded by the "oil rock."

2. The general localization of ore above, below, and in the "oil rock" is attributed to faulting and fracturing which is best

developed along the borders of that and the immediately subjacent highly plastic horizons, where lateral compression would induce plastic deformation of the shale, but would fracture the adjacent, more rigid limestone; such fractures might well extend to higher or lower beds also but would probably split and so lose their distinctness.

3. Chemical and mineralogic data make deposition by descending waters the more difficult hypothesis. Supporting evidence is found in such studies as those of Newhouse [31] and of Graton and Harcourt.[32]

4. In view of the nature of the inclusions as reported by Newhouse,[33] the negative ions in the mineralizing solutions would seem to have been the chloride and probably also the sulphide.

5. Deposition was apparently caused by cooling of the solutions as they rose. It was not conspicuously confined to a single stratigraphic horizon, as already pointed out above. The generally horizontal position and parallelism between the present surface, the ancient peneplain surface, and the upper levels of ore deposition is a striking feature on which others [34] have commented. Such a correspondence may well be due to the mingling at a fairly constant depth below the surface of the ascending ore-bearing with the descending meteoric waters. The result would certainly be a cooling of the former, and probably also the setting off of some chemical reaction not as yet understood. In this sense, there would appear to be a definite relation between the physiographic history of the region and the ore deposition.

6. As suggested by the marcasite-pyrite relations in the veins, deposition was modified through neutralization of excess chloride ions by reaction with the country rock. This would be anticipated from the work of Allen, Crenshaw, and Merwin and their

[31] Newhouse, W. H.: The composition of vein solutions as shown by liquid inclusions in minerals. ECON. GEOL., vol. 27, pp. 428–436, 1932. Newhouse, W. H.: The temperature of formation of the Mississippi Valley lead-zinc deposits. ECON. GEOL., vol. 28, pp. 748–749, 1933.

[32] Graton, L. C., and Harcourt, G. A.: Spectographic evidence on origin of ores of Mississippi Valley type. ECON. GEOL., vol. 30, pp. 800–822, 1935.

[33] *Op. cit.*, 1932.

[34] *E.g.*, Bain, H. F.: *Op. cit.*, p. 69, 1906.

associates.[35] The former presence of wurtzite also bears out the assumption of acidity in the solutions.

7. The vertical zoning of the lead and zinc sulphide already mentioned is not explicable in simple terms, despite Ridge's[36] excellent attempt for the Tri-State district, but it is not an uncommon feature in other districts where the ore has been assigned to rising, thermal solutions.[37] This zoning is thus consistent with deposition by rising solutions.

8. After deposition much of the iron sulphide and virtually all of the zinc sulphide changed slowly from their more unstable (marcasite, wurtzite) to their more stable (pyrite, sphalerite) forms. This is suggested by their relations, the crystal forms shown, and the analogous observations by Ehrenberg, cited above.

In closing, the writers wish to disclaim finality for the arguments just outlined. We recognize that, as recently well emphasized by Leith,[38] there is a strong tendency for each observer to interpret a given set of facts in the light of his own experience, and thus fall victim to prejudice. It is this difficulty in methodology that still faces our science. Yet generalizations are the soul of progress, and as such are merited, however tentative. In any case, the *facts* appear to be as stated and may, it is hoped, serve other observers in framing possibly sounder hypotheses.

NORTHWESTERN UNIVERSITY,
EVANSTON, ILLINOIS,
April 27, 1937.

[35] Allen, E. T., Crenshaw, J. L., and Merwin, H. E.: Effect of temperature and acidity in the formation of marcasite (FeS_2) and wurtzite (ZnS), etc. Am. Jour. Sci., 4th ser., vol. 38, pp. 430–431, 1914.

[36] Ridge, John: The genesis of the Tri-State zinc and lead ores. ECON. GEOL., vol. 31, pp. 303, 310–311, 1936.

[37] Spurr, J. E.: Theory of ore deposition. ECON. GEOL., vol. 7, p. 489, 1912. Emmons, W. H.: Primary downward changes in ore deposits. Am. Inst. Min. Eng., vol. 70, pp. 983, 987, 1924.

[38] Leith, C. K.: Structures of the Wisconsin and Tri-State lead and zinc deposits. ECON. GEOL., vol. 27, pp. 406–410, 1932.

PARAGENESIS OF IRON SULPHIDES IN A BLACK HILLS DEPOSIT.

G. M. SCHWARTZ.

ABSTRACT.

A small prospect mine near Deadwood, South Dakota, shows striking selective replacement of dolomite beds by quartz, pyrite, sphalerite, arsenopyrite, galena, chalcopyrite, and pyrrhotite. The occurrence of arsenopyrite, pyrrhotite, and gold values is significant in view of the occurrence of these minerals in the Homestake Mine, three miles distant.

The remarkable feature of the ores is the abundant occurrence of four types of iron sulphide aside from small amounts of pyrrhotite. These varieties are: aggregates of anhedral grains of pyrite; euhedral pyrite crystals; stippled, brownish, fine-grained pyrite, and marcasite. The stippled brownish variety of pyrite is believed to have formed by alteration of pyrrhotite at a late stage in the mineralization apparently after the partial replacement of pyrrhotite by marcasite.

INTRODUCTION.

For many years the writer has periodically visited with a field class a small zinc-lead prospect in the Black Hills near Deadwood, South Dakota. This first attracted attention because it shows selective replacement of dolomite beds in a remarkably diagrammatic fashion. Later J. L. Middleton worked on the microscopic features of the ores as a thesis problem and the unusual nature of the pyrite came to light. Only recently the writer has, by analogy with ore from another district, arrived at what is believed to be the correct explanation of the origin of some of the peculiar pyrite and marcasite. The ore also is significant because it contains abundant arsenopyrite, an important mineral in the Homestake ore body only three miles distant. If the suggestion that some of the pyrite and marcasite was derived from pyrrhotite is accepted, then the deposit is still more significant because pyrrhotite is used as one of the main arguments for the pre-Cambrian origin of the Homestake ores. The ore here described is clearly Tertiary in origin.

LOCATION.

The Deadwood Zinc and Lead Mine is in reality a prospect, as it has not been a commercial producer. It is located in Spruce Gulch about three-fourths of a mile from its mouth, just below the city of Deadwood. The location is on the road between the old mining town of Two Bit and Deadwood. This is in an area of Paleozoic rocks intruded by Tertiary porphyries. Emmons [1] has shown the areal relation to other deposits of the region.

DEADWOOD FORMATION.

The deposit occurs in a series of dolomitic beds interbedded with shale which belong to the Deadwood Formation. The Deadwood comprises the Cambrian beds of the Black Hills region and is described in some detail by Darton and Paige.[2] The type section of the Deadwood is a mile from the Deadwood Zinc and Lead Mine, but poor exposures between, and the occurrence of Tertiary sills and other intrusives, makes the exact horizon of the deposits uncertain. It is probable that the replaced beds are near the middle of the formation.

The Deadwood in the northern portion of the Black Hills consists of a massive cross-bedded, buff sandstone with some conglomerate at the base and a considerable thickness of interbedded impure dolomitic beds, greenish shales, sandstone, and glauconitic beds above. Near the top is a conspicuous quartzitic sandstone bed with worm borings. At Deadwood and elsewhere the contact with the underlying metamorphic rocks is exposed at many places.

In the northern Black Hills many gold deposits have been opened in various horizons of the formation. In fact, the bulk of the gold production of the Black Hills region aside from that of the Homestake Mine, has come from mineralized beds in this

[1] Emmons, W. H.: Metalliferous lode systems and igneous intrusives. Am. Inst. Min. Met. Engr. Trans., vol. 74, p. 37, 1926.

[2] Darton, N. H., and Paige, Sidney: Central Black Hills, South Dakota. U. S. Geol. Surv. Folio 219, 1925.

formation. Irving's description of these deposits is a classic in the literature of ore deposits.[3]

Thin sections of a number of phases of Deadwood formation from the mine and from exposures near the portal show the variety of material. Evidently the horizon is one in which glauconite is not important as only one slide showed a small amount. The carbonate ranges from extremely fine grained to fairly coarse grained material. Fossil fragments are rather common. Gradation from carbonate to silty bands was also noted and flat-pebble beds are numerous.

The mineralized specimens show various stages of replacement by pyrite and sphalerite, accompanied by the introduction of quartz. Much of the quartz is a fine grained cherty variety, but euhedral crystals are abundant in the ore.

TERTIARY PORPHYRY.

The Black Hills series of porphyries of Tertiary age shows about as complete a group of rock types as can be found anywhere They comprise also a complicated series of forms; dikes, sills, laccoliths and various intermediate forms. These are described in considerable detail by Darton and Paige.[4]

The rock that is penetrated by the lower drift of the mine is a monzonite porphyry. A small amount of quartz may be seen in thin section, but not enough to class the rock as quartz monzonite. The freshest specimen available is medium grained with medium to small plagioclase phenocrysts. The matrix is fine grained and altered somewhat to kaolinite. The ferromagnesian minerals were probably scant and have disappeared during alteration.

In most specimens of the porphyry the feldspar is much altered to sericite. There are also titanite, leucoxene, chlorite, limonite, kaolin and disseminated pyrite. A specimen from the hill above the mine contains medium to small plagioclase phenocrysts, with numerous small hornblende crystals in the groundmass, which is essentially like that of the porphyry in the mine.

[3] Irving, J. D.: Economic resources of the northern Black Hills. U. S. Geol. Surv. Prof. Paper 26, 1904.

[4] *Op. cit.*, page 16.

STRUCTURE.

The beds of the Deadwood formation containing the ore have a fairly regular monoclinal dip of 12 to 13 degrees northeast, with a strike about N. 25° W. (Figs. 1–2). In a small drift from the bottom of the stope just above the ore chute a fault contact with porphyry is exposed. This is known to be a fault because the beds are not baked and hardened as at an intrusive contact, but are broken and decomposed and the face of the porphyry is smooth as if slickensided. The downthrow side of the fault is on the east or porphyry side, as the Cambrian beds are dragged down against the porphyry. This likewise shows that the porphyry is not the same intrusive as the sill penetrated by the lower tunnel. It is probably a sill intruded at a higher stratigraphic position in the Cambrian beds. One or more sills occur on the hill above the mine. The lower porphyry is apparently a sill, but the beds are transgressed somewhat as is shown by the fact that the distance between the porphyry below, and the heavy shale above the ore increases down the dip from the portal of the upper workings.

The ore seems to have been definitely limited above by the existence of a heavy shale bed several feet thick. This shale apparently ponded the solutions, forcing them to spread laterally and deposit their load by replacing the soluble dolomitic beds. Definite fractures, which are a conspicuous feature of the gold deposits in the Black Hills Cambrian beds, as shown by Irving,[5] were not recognized in the ore, but the abundance of vertical fractures in the porphyry beneath and the narrow sulphide feeder veins leave no reasonable doubt that the solutions did gain access to the dolomitic beds along nearly vertical joints from which they spread laterally.

CHARACTER OF THE ORE.

The ore consists of fairly massive irregular dolomitic beds some of which were flat-pebble conglomerates. These beds have been rather completely replaced by sulphides and quartz. Many

[5] *Op. cit.*

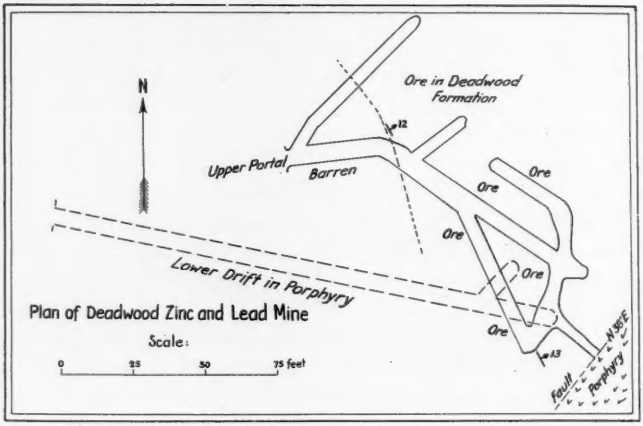


Figure 1

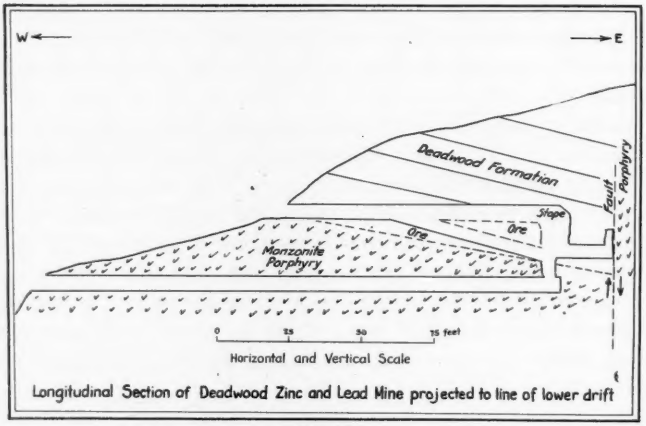


Figure 2

of the beds contain practically no residual carbonate or other original minerals, but the texture and structure of the replaceable beds have been so faithfully preserved that they may be said to be pseudomorphically replaced. Equally as striking as the replacement of the dolomitic beds is the absence of replacement of the

thin shale beds between. It is an excellent example of selective replacement. Following is a detailed section, measured in the stope where the greatest vertical exposure of sulphide ore occurs. The alternation of shale and carbonate beds replaced by sulphide is well shown by these measurements.

Vertical Section in Stope Over Shoot to Lower Tunnel.

Capping shale 12″ exposed	
3″	sulphide
1″	shale
15″	mostly sulphide, thin shale
6″	sulphide
2″	shale
8″	sulphide
24″	shale, sulphide, mixed in thin bands
12″	sulphide
3″	shale
6″	sulphide
¼″	shale
4″	sulphide (flat pebble structure)
20″	shale, sulphide, etc.
¼″	shale
5″	sulphide
¼″	shale
1½″	sulphide
2″	shale
4″	sulphide
1″	shale
4″	sulphide
3″	shale
8″	sulphide, shale, etc.
3″	sulphide
½″	shale
1½″	sulphide
1½″	shale
5″	sulphide
12″	shale
Porphyry sill.	

Assay of channel sample to accompany section. Zinc 6.06 per cent.; lead 1.13 per cent.; gold (oz.) .12; silver (oz.) 3.64. Assay by R. J. Leonard.

Veinlets carrying mainly sphalerite cut across the shale beds at places suggesting that the last mineralizing solutions carried mainly zinc sulphide, but arsenopyrite crystals were found in a vug with sphalerite. Many small veinlets and stringers of sphalerite occur in the porphyry in the lower tunnel. The mineraliza-

tion is thus distinctly post porphyry in age as is suggested by the hydrothermal alteration of the porphyry.

Assays of several samples are available. The following give an idea of the composition of the best sulphide material, that is, where replacement of the Deadwood formation has been most complete. This average is probably well above the average that could be mined because of the necessary inclusion of much shale and lean ore in mining.

Gold	Average of 15 assays	.18	ounces
Silver	Average of 15 assays	4.66	ounces
Lead	Average of 13 assays	2.9	per cent
Zinc	Average of 14 assays	7.3	per cent
Sulphur	Average of 3 assays	15.2	per cent
Arsenic	Average of 3 assays	2.54	per cent
Iron	Average of 6 assays	19.2	per cent

The polished surfaces of the ore present a great variety of textures and structures, even within a single specimen. This is in part due to the original variable character of the dolomite. The flat pebbles, for example, present a much finer grained texture than the matrix. Bedding is commonly preserved in the sulphides.

Iron Sulphides.

Pyrite and marcasite form a considerable portion of the ore and show a variety of forms. The following classification gives a fair idea of the types of iron sulphide.

Type I. Aggregates of anhedral grains of pyrite.
Type II. Euhedral pyrite crystals.
Type III. Stippled brownish pyrite; apparently very fine grained.
Type IV. Marcasite along borders and penetrating Type III.

All of these types of iron sulphide are common and frequently all four may be observed within a single microscopic field, using a 16 mm. objective. Each has its own characteristics and can be distinguished at a glance. No-relief polishing brings out the relations much better than is possible where relief is developed.

Type I.—This type consists of aggregates of euhedral grains and is the most abundant of the four types. The shapes of the aggregates differ widely. Fig. 3 shows a common texture with elongated, somewhat branching pyrite aggregates. The reason for these peculiar shapes is not evident from anything that could be discovered in the specimens, but they are quite characteristic. The most reasonable assumption is that they follow structures in the original dolomite. Generally the anhedral grains are grouped in irregular areas as is common in many ores. Some specimens consist of anhedral pyrite with only a small amount of sphalerite and insignificant amounts of other minerals.

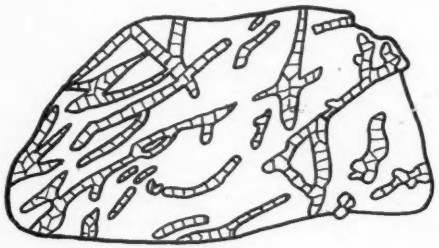


FIG. 3. Sketch of polished surface showing peculiar elongated aggregates of anhedral pyrite. Grain boundaries indicated. Matrix mainly sphalerite. ×2.

A peculiar feature of these anhedral pyrite grains is that they are distinctly anisotropic, from greenish to purplish in color. The grains appear of two kinds in plain light, one with the usual brassy color of pyrite and the other of a distinctly lighter tint. Under polarized light they appear the same, although the grains are differently oriented as indicated by the colors under polarized light.

Pyrite is listed by Short [6] as sometimes anisotropic, but not as highly so as these specimens. Van der Veen [7] mentions that some pyrite is anisotropic, and Schneiderhöhn says that aniso-

[6] Short, N. M.: Microscopic determination of the ore minerals. U. S. Geol. Surv. Bull. 825, p. 98, 1931.

[7] Van der Veen, R. W.: Mineragraphy and ore deposition, p. 34, 1925.

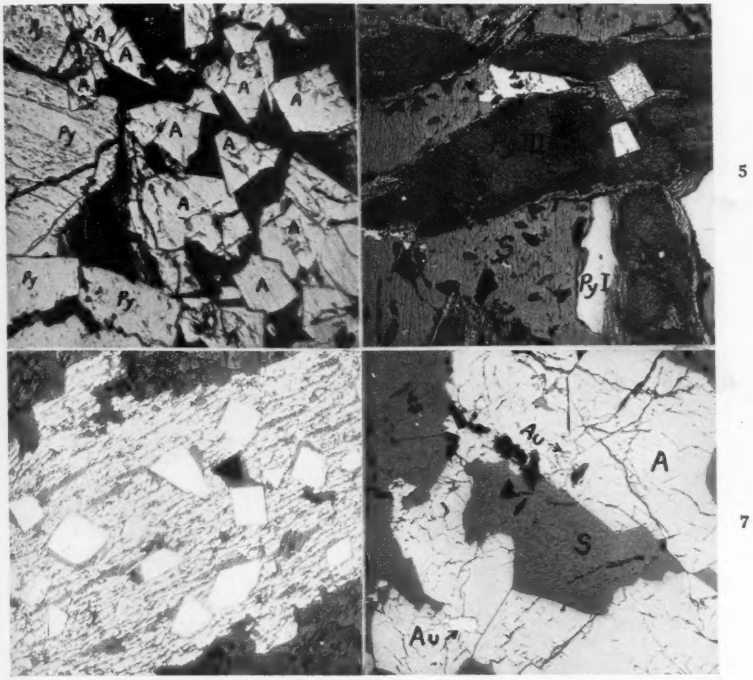
tropic pyrite contains arsenic.[8] This seems to offer a logical explanation of such anomalous pyrite, much of which is lighter colored than normal and definitely anisotropic. The close association of pyrite with arsenopyrite in the Deadwood deposit is evidence of the availability of arsenic (Fig. 4).

The anhedral pyrite appears to have crystallized at an early stage in the mineralization as there is a lack of evidence of its being later than any other sulphides. It seems contemporaneous with arsenopyrite and is only slightly attacked by sphalerite and galena.

Type II.—Euhedral pyrite crystals are much less common than the anhedral grains. Their characteristic occurrence is in areas of pyrite of Types III and IV as isolated euhedral crystals (Fig. 5). It seems impossible to distinguish any age difference between these crystals and the anhedral grains. Probably a reasonable assumption is that they are of the same age, but isolated crystals grew to euhedral form because of a lack of interference. The matrix may have been the original carbonate rock or sulphides that replaced the rock. The crystals are generally much smaller than the anhedral grains and this and their shape distinguish them from Type I. The most common occurrence of the euhedral crystals is in the fine grained pyrite, Type III (Fig. 6). Euhedral pyrite was also observed in sphalerite, galena, and carbonate.

Type III.—This type has a decidedly brownish color and maintains a stippled surface even with no-relief polishing. No method was found that would give a smooth surface, but long polishing on buffing wheels does eliminate most of the roughness and the color becomes nearly that of ordinary pyrite. The material is completely isotropic and extremely fine grained. This type is abundant in only part of the specimens studied. It is characteristically surrounded and penetrated by marcasite (Type IV) but the fact that marcasite was evidently controlled by a linear structure that is not present in Type III suggests that the mar-

[8] Schneiderhöhn, H.: Mineralchemische und mikroskopische Beobachtungen an Blei-Zink- und Krieserzen. Chemie der Erde, vol. 5, pp. 390–392, 1930. Schneiderhöhn, H., and Ramdohr, P.: Lehrbuch der Erzmikroskopie, vol. 2, p. 159. Berlin, 1931.



4 5 6 7

FIG. 4. Anhedral pyrite (Py) and anhedral to euhedral arsenopyrite (A) in mutual relation. × 40.

FIG. 5. Euhedral pyrite crystals in fine-grained pyrite which is slightly replaced along borders by marcasite (M). Sphalerite (S), Anhedral pyrite (Py. I). × 50.

FIG. 6. Euhedral pyrite crystals in an intergrowth of marcasite and carbonate. × 100.

FIG. 7. Sphalerite (S) and arsenopyrite (A) in mutual relation. Gold in arsenopyrite (Au). × 40.

casite replaced a pre-existing mineral. This mineral is believed to have been pyrrhotite. The writer has described and figured [9] an identical texture with pyrite replacing pyrrhotite. This is a

[9] Schwartz, G. M.: The paragenesis of pyrrhotite. ECON. GEOL., vol. 32, p. 36, Figs. 5 and 6, 1937.

peculiar texture involving the replacement of pyrrhotite by pyrite and carbonate. It would be remarkable if an exactly similar texture should have developed from another original mineral. It is believed, therefore, that the parting of pyrrhotite c(0001) guided the replacement. In the Deadwood ore after partial replacement at places conditions changed and the residual pyrrhotite was changed in mass to fine grained brownish pyrite. Under high magnifications certain areas seem to show partial conversion of pyrrhotite to pyrite. This brownish pyrite is therefore the last mineral to form if the above interpretation is correct.

Type IV.—The fourth type of iron sulphide is classified as marcasite on the basis of its anisotropism, which agrees exactly with that of known marcasite. The fact that it is lighter in color than the other varieties also is indicative. Marcasite in this ore, without exception, has a characteristic occurrence such as is illustrated in Fig. 6. Enclosed euhedral pyrite crystals are common in some areas, but are absent in many others. The marcasite occurs in zones around the brown pyrite (Type III) and apparently penetrates it along original partings.[10] Marcasite seems everywhere to be accompanied by siderite or ankerite. The replacement of the earlier material is complete in many specimens, leaving no remnants of Type III. The marcasite was evidently controlled by the pre-existing minerals as it was not observed to form grains of varied shapes or of its own crystal form, but only the characteristic elongated blade or spindle shaped areas. Many euhedral quartz crystals are embedded in the marcasite-carbonate areas, cutting both minerals. The age relation is not evident.

Arsenopyrite.—Polished surfaces, especially those polished by the no-relief method, show a surprising amount of arsenopyrite. The actual percentage may be roughly estimated at 5.5 per cent from the arsenic content (2.54 per cent) of three channel samples. Inasmuch as the sulphide content of this ore was approximately 50 per cent, the arsenopyrite makes up about 11 per cent of the ore minerals.

The arsenopyrite occurs as fairly coarse subhedral to euhedral

[10] Compare with ECON. GEOL., vol. 32, p. 36, Fig. 5.

grains commonly intergrown with pyrite. The euhedral grains tend to occur in carbonate or other gangue minerals. The practically mutual occurrence with Type I pyrite suggests that the two are contemporaneous.

In one specimen arsenopyrite and sphalerite occur almost to the exclusion of other sulphides and native gold was recognized in the arsenopyrite (Fig. 7). One specimen shows a late vein

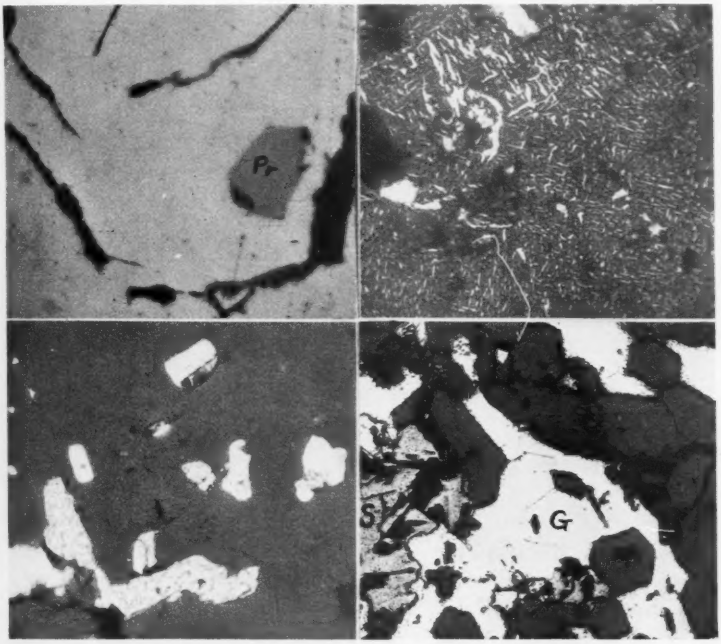


FIG. 8. Pyrrhotite (Pr) inclusion in arsenopyrite. × 550.

FIG. 9. Chalcopyrite inclusions in sphalerite. Some oriented along crystallographic directions. × 960.

FIG. 10. Pyrrhotite inclusions in sphalerite. Those in lower left hand area altered to pyrite. × 960.

FIG. 11. Euhedral to subhedral quartz crystals in galena (G) with sphalerite (S).

crossing a replaced bed with vugs that contain both sphalerite and arsenopyrite crystals, thus showing that both minerals formed during the last mineralization. Where arsenopyrite borders sphalerite or galena, many grains appear to have been attacked by these sulphides (Fig. 12). Thus a crystal bordering carbonate on one side will have a straight crystal face, whereas on the other it will be in irregular contact with sphalerite or galena. Marcasite cuts across some arsenopyrite grains, about the only cross-cutting relation observed except that marcasite cuts pyrite III. It is probable that the sulphides just referred to replace the arsenopyrite, but the possibility that the crystals failed

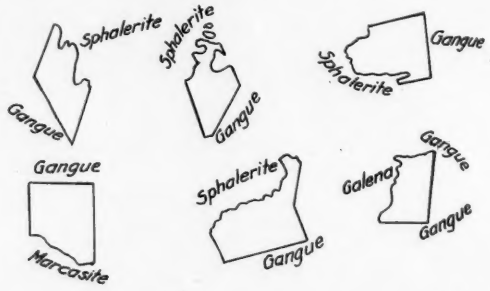


FIG. 12. Outlines of arsenopyrite grains showing euhedral form adjacent to gangue and corroded appearance bordered by sphalerite, galena, and marcasite. × 100.

to develop euhedral form when crystallizing next to other sulphides, must be considered. Many arsenopyrite crystals show no evidence of replacement by other sulphides.

Sphalerite.—The most abundant sulphide, aside from pyrite, is sphalerite. The average assay indicates that it forms 10.7 per cent of the ore or over 21.4 per cent of the sulphides. It occurs as a sort of matrix to the anhedral or euhedral pyrite and arsenopyrite grains and the peculiar lens-shaped areas of brown pyrite and marcasite. The sphalerite appears nearly contemporaneous with pyrite and arsenopyrite, but seems to have attacked some of them, as noted above in the description of arsenopyrite. Cross

veins of sphalerite in the ore and small veins in the porphyry suggest that sphalerite was deposited as the final stage of mineralization accompanied, in one vug that was observed, by arsenopyrite. These cross veins are local and do not indicate a late origin for the bulk of the sphalerite as it was not observed cutting other sulphides as veinlets in the polished surfaces.

Much of the sphalerite contains myriads of chalcopyrite inclusions visible only at magnifications of 800 to 1000 diameters (Fig. 9). Associated with some of these inclusions are larger pyrrhotite inclusions (Fig. 10). Some grains of sphalerite appear somewhat yellowish in color, due to the abundance of inclusions. A conspicuous feature of some specimens is that these inclusions are crowded in the interior of the grains of sphalerite, whereas the borders are entirely free from them. Most of the inclusions are round to irregular in outline, but in places they are blade-like and form a lattice-like intergrowth.

Galena.—The amount of galena is generally small and its relations are clear only on no-relief surfaces. All the galena occurs with sphalerite and appears to be essentially contemporaneous with it. The areas are irregular in outline, are of various sizes, and have mutual boundaries with sphalerite. Inclusions of other minerals are not common in galena except that euhedral to subhedral quartz crystals are locally abundant. As noted above, galena seems to replace arsenopyrite to a limited extent. A little was found replacing pyrite also, but this is not common.

Chalcopyrite.—The presence of chalcopyrite in hand specimens can be suspected only where oxidation has formed green malachite. Microscopic examination, however, reveals small amounts of chalcopyrite as the inclusions in sphalerite noted above, and as occasional small areas associated with sphalerite and with the brown iron sulphide (Type III). Certainly most of the chalcopyrite, if not all, is contemporaneous with sphalerite. The inclusions have usually been interpreted in other occurrences as having resulted from ex-solution of copper sulphide dissolved in the zinc sulphide at higher temperatures.

Pyrrhotite.—The presence of pyrrhotite was suspected from

the texture of the marcasite-carbonate areas. The mineral was recognized only as inclusions in arsenopyrite and sphalerite. The brown pyrite (Type III) and marcasite are believed, as indicated above, to have formed by partial replacement of pyrrhotite by marcasite and carbonate and subsequent alteration of the residual pyrrhotite to pyrite. The inclusions of pyrrhotite in arsenopyrite and sphalerite were no doubt protected by the host minerals and thus escaped alteration to pyrite (Type III). The occurrence of pyrrhotite is suggestive of somewhat higher temperature of origin than has usually been assigned to these deposits and is important in correlation of the deposits of the northern Black Hills.

Quartz.—The occurrence of quartz has been referred to frequently in the descriptions of the various minerals. The introduction of considerable amounts of silica was a characteristic feature of the mineralization. In some specimens quartz actually predominates, but in most it is subordinate to the sulphides. At places it makes a practically solid mass, but its more striking occurrence is as euhedral to subhedral crystals in the carbonate, galena, sphalerite, marcasite and brown pyrite areas. The introduction was evidently contemporaneous with the introduction of the sulphides. Skeletal crystals of quartz, for example, include sulphides and are in turn surrounded by them.

Summary of Order of Formation.—The order of formation of minerals is by no means evident. To a considerable extent this seems due to the fact that the various sulphides formed so nearly at the same time.

Pyrite (I and II) and arsenopyrite are contemporaneous so far as can be determined. Sphalerite seems contemporaneous with them, in part, although the fact that it tends to assume a matrical position makes it look later. In fact sphalerite and galena have been classed as later in a previous paper.[11] Sphalerite also seems to corrode arsenopyrite and to a lesser degree pyrite. It is probable that much sphalerite formed contemporaneously with pyrite and arsenopyrite with some overlap. The last min-

[11] Connolly, J. P.: The Tertiary mineralization of the northern Black Hills: S. Dak. School of Mines Bull. 15, p. 110, 1927.

eralization was mainly sphalerite as shown by small cross-cutting veins.

Chalcopyrite and pyrrhotite appear contemporaneous with sphalerite, generally occurring as inclusions. The pyrrhotite now altered to marcasite was probably also contemporaneous with sphalerite.

Pyrite III and marcasite present a difficult problem. The writer believes that Pyrite III and the marcasite-carbonate areas represent original pyrrhotite areas. The pyrrhotite was partly replaced along parting planes by marcasite and carbonate. At places the replacement was complete. Where pyrrhotite was not completely replaced by marcasite, a change in physical-chemical conditions converted it *en masse* to the brownish, fine-grained pyrite (Type III).

In brief the order is: pyrite, types I and II, and arsenopyrite earliest, with sphalerite, galena, chalcopyrite, and pyrrhotite in part contemporaneous, but deposition continuing beyond that of pyrite and arsenopyrite. Marcasite formed next, probably by replacement of pyrrhotite, followed by conversion of pyrrhotite to pyrite (Type III) with some sphalerite deposited at a late stage with at least a little arsenopyrite and small amounts of other minerals.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
May 14, 1937.

A PYRRHOTITE RUBY SILVER OCCURRENCE IN BRITISH COLUMBIA.

HARRY V. WARREN AND KENNETH DE P. WATSON.

ABSTRACT.

At the Providence Mine near Greenwood in Southern British Columbia ruby silver and pyrrhotite occur in intimate association. Associated with these minerals are sphalerite, galena, chalcopyrite, tetrahedrite, quartz, and calcite. Chalcopyrite and ruby silver are closely related, and have in part replaced pyrrhotite, which is older. Nevertheless, the boundaries of all three minerals show smooth, rounded contacts, and the evidence points to their having been deposited within a short time of one another.

ALTHOUGH many occurrences of hypogene ruby silver have been described, none of these seem to contain ruby silver and pyrrhotite in intimate association. The following brief description of the Providence mine in B. C. may therefore prove of interest, as this association is found in the ore of the mine.

LOCATION AND GEOLOGY.

The Providence mine is situated on the western slope of the valley of Boundary Creek at a point about one mile north of the town of Greenwood, which lies close to the International Boundary about midway across British Columbia.

The ore of the Providence mine occurs in a narrow fissure vein that cuts a series of rocks, probably Palæozoic in age. These rocks consist of augite porphyrites, agglomerates, and porphyrite tuffs, all of which have been so highly metamorphised that it is impossible to determine their structure. In places, the Providence vein cuts irregular granodioritic masses that are thought to be part of a large batholith, known as the Greenwood Batholith, which outcrops about 500 feet from the mine and is believed to be indirectly related to many of the ore deposits in the Greenwood district.

The vein, which varies in width from 6 to 18 inches, is cut by numerous faults of small displacement. The vein is also cut by a few post-mineral porphyry dikes.

During a sporadic life, which commenced in 1896, the Providence mine has shipped several thousand tons of gold silver ore. A 50-ton mill was erected in 1934. Until 1936 no work had been done below the 500-foot level.

MINERALOGY OF THE ORE.

The following list gives, in order of abundance, the minerals that were identified in polished sections of ore from the Providence mine: quartz, calcite, sphalerite, galena, chalcopyrite, tetrahedrite, ruby silver, pyrrhotite.

All these minerals, with the exception of tetrahedrite and pyrrhotite, can readily be seen megascopically. A small particle of pyrite in quartz was identified in one hand specimen. Pyrite is abundant in many nearby properties.

The quartz is milky white inclining to grey, microcrystalline, and is veined and invaded by all the other minerals found in the ore with the possible exception of pyrite, which, from the scanty evidence available in this suite is probably of the same age as the quartz, as is the case elsewhere in this district. The calcite is mostly coarsely crystalline; it may be white but grey is the most characteristic color. In places, the calcite is surrounded by quartz but more commonly it fills obvious fractures and is younger. Probably there was considerable overlapping in the deposition of these two minerals with, however, the calcite deposition persisting for some time after that of the quartz had ceased.

Sphalerite is the most conspicuous metallic mineral in the ore. It is generally dark brown to black in color. Megascopically it is remarkably free from impurities. A sample of this material, carefully picked by hand, was assayed and found to carry 7.82 ounces of silver per ton. Representative fragments taken from the material that was chosen for assay were polished, examined microscopically, and found to contain several minute blebs of tetrahedrite and galena. The contacts between the galena, tetra-

hedrite and sphalerite are smooth, regular curves indicating that the three minerals were, in this place, deposited contemporaneously. Sphalerite occurring both in quartz and in calcite gangues shows similar relationship with galena and tetrahedrite.

Chalcopyrite occurs in visible grains and microscopically in irregular minute blebs in the sphalerite in a manner identical to that of galena and tetrahedrite. However, chalcopyrite was noticeably absent in much of the sphalerite. It is also interesting that the chalcopyrite generally includes rounded blebs of sphalerite, and the two minerals commonly are found with smooth rounded boundaries veining calcite.

Galena is conspicuous in some places but tetrahedrite is seen only under the microscope and occurs either as minute rounded blebs in galena or as larger masses in sphalerite, commonly in contact with galena.

Ruby silver is one of the younger if not the youngest mineral present and is found most commonly in contact with calcite or chalcopyrite. In calcite it generally occurs in minute veinlets that are clearly controlled by the rhombohedral cleavage of the carbonate. In one section it was seen lying between a euhedral quartz crystal and a surrounding mass of calcite. Although it does occur with galena and sphalerite it generally is in contact with chalcopyrite, which in turn commonly contains, and in places appears to replace pyrrhotite.

Pyrrhotite, unsuspected in megascopic examinations, was noted frequently under the microscope, although in relatively small amounts. It is most commonly closely associated with chalcopyrite, with mutually rounded boundaries but it is also similarly related to the ruby sliver. In fact, the common association of these three minerals in the samples studied was most noticeable. Pyrrhotite apparently has been replaced by these chalcopyrite in some areas. The pyrrhotite is present in quantities too small to attempt microchemical analyses, separation from possible contamination being impossible. The characteristic color and definite etching tests, however, make its determination certain.

In one section where a ruby silver veinlet follows a calcite cleavage crack it contains both chalcopyrite and pyrrhotite and the

boundaries between all the minerals are smooth and "mutually" rounded. There would seem to be little doubt but that here all three minerals were deposited contemporaneously.

The relationships described above are illustrated in Figs. 1–4.

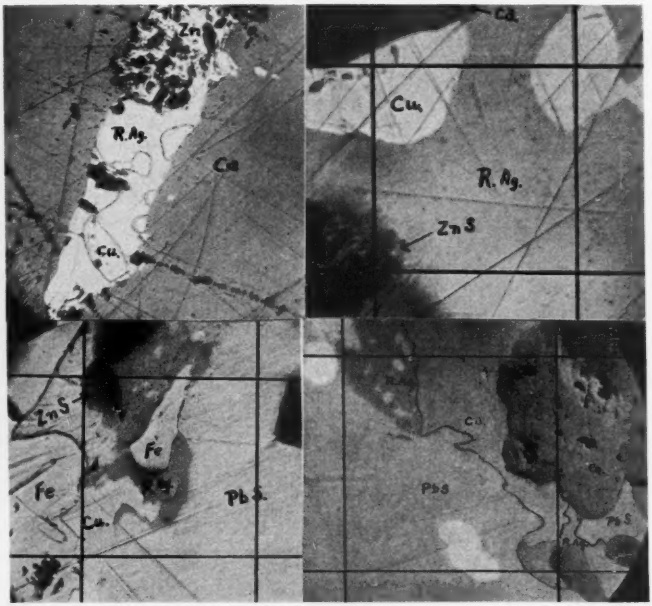


FIG. 1. Ruby silver (R. Ag.), chalcopyrite (Cu), and sphalerite (Zn) occupying a fracture in calcite (Ca). × 100.

FIG. 2. Photomicrograph showing the smooth fresh contacts between chalcopyrite (Cu) and ruby silver (R. Ag.). ZnS—sphalerite. Ca—calcite. 200 mesh grid superimposed. × 500.

FIG. 3. Photomicrograph showing galena (PbS), chalcopyrite (Cu), pyrrhotite (Fe), ruby silver (R. Ag.), and sphalerite (Zn). 200 mesh grid (.074 mm. opening) superimposed. × 420.

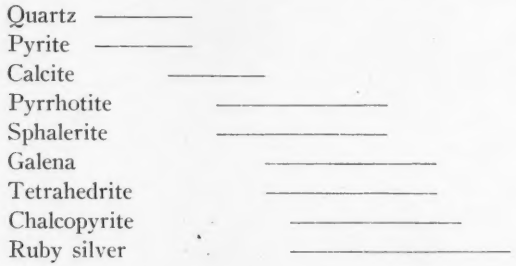
FIG. 4. Photomicrograph showing galena (PbS), chalcopyrite (Cu), pyrrhotite (Fe), ruby silver (R. Ag.), and sphalerite (Zn). 150 mesh grid (.104 mm. opening) superimposed. × 360.

PARAGENESIS.

Summing up the evidence, the sequence of events seems to have been as follows:

1. Deposition of quartz and pyrite in a fracture in the country rock.
2. Fracturing of the quartz.
3. Deposition of calcite in fractures and vugs in the quartz vein.
4. Fracturing of the quartz and calcite.
5. Deposition of pyrrhotite, sphalerite, galena, tetrahedrite, chalcopyrite and ruby silver in fractures in the quartz and calcite.

This sequence is represented graphically in the following table:



ORIGIN OF THE RUBY SILVER.

Because ruby silver may be either hypogene or supergene, special attention was given to the determination of its origin in the Providence deposit. It is believed to be hypogene from the following evidence:

(1) It is found in contact with galena, chalcopyrite, tetrahedrite, pyrrhotite, and sphalerite and the contacts are generally mutually rounded.

(2) None of the minerals such as chalcopyrite or pyrrhotite show any evidence of having been subjected to the action of descending meteoric waters.

(3) There is no sign of any characteristic supergene mineral

in the vicinity of the ruby silver observed in any one of the polished sections. Such minerals as covellite, bornite, cerussite, and smithsonite being conspicuous by their absence.

Pyrrhotite-Ruby Silver Relationship.—The association in the ore of pyrrhotite and primary ruby silver is noteworthy. Pyrrhotite is customarily thought of as having been formed under hypothermal conditions. The evidence cited above, however, suggests that probably pyrrhotite can be deposited under conditions of relatively low temperature; its association with ruby silver, which is considered to be a definitely low temperature mineral might be explained by sudden cooling which produced a "telescopic" effect in the crystallization of the various minerals. There appears no positive evidence to support this contention.

The deposit may be assigned to Graton's telethermal zone but the authors merely put this forward as a suggestion.

ACKNOWLEDGMENTS.

The authors wish to express their appreciation to L. Madden of the Providence mine for the donation of the specimens examined in this study.

All of this work with the exception of the assaying was done in the laboratories of the Department of Geology and Geography of the University of British Columbia. The silver assay was done in the laboratories of the Department of Mining and Metallurgy; to this Department the authors wish to express their thanks. The authors also wish to express their appreciation to Dr. C. O. Swanson for his advice and criticism in the preparation of this paper.

UNIVERSITY OF BRITISH COLUMBIA,
VANCOUVER, B. C.,
June 5, 1937.

THE ORE DEPOSITS OF THE SUNLIGHT MINING REGION, PARK COUNTY, WYOMING.

WILLARD H. PARSONS.

ABSTRACT.

The Sunlight mining region lies in the Absaroka Mountains, Wyo. The deposits are twenty miles from the nearest road and are not developed. The mineralization is genetically associated with an intrusive and volcanic center made up of a small stock of syenite and diorite, several basaltic plugs, hundreds of radially-arranged dikes, and a few cone sheets, all in the Early Basic Breccia Series of the Absarokas. The deposits are small, irregular fissure veins in fault zones and along dike contacts in the Tertiary Volcanic breccias.

The common ore minerals are pyrite, chalcopyrite, galena, and tetrahedrite with pockety values in gold and silver. The gangue is essentially carbonates and quartz. The deposits have the banded and vuggy character of typical epithermal veins; they exhibit a vertical zoning that is well exposed due to the 3,000 foot relief, and seems to have been dependent on a vertical temperature gradient that existed in the roots of the volcano shortly after its activity had ceased. In the deepest zone are pyrite-quartz veins and above them successively, chalcopyrite-pyrite-gold, chalcopyrite, galena, and galena-silver veins in a 2,000 foot range.

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INTRODUCTION.

THE Sunlight mining region is in the heart of the northern Absaroka Mountains in the Shoshone National Forest, Park County, Wyoming. Its ore deposits occur in the cirque basins and on the ridges at the headwaters of various branches of Sunlight Creek and the North Fork of the Shoshone River, about six miles from the eastern boundry of Yellowstone National Park. This region may be reached only by Forest Service trails. It is twenty miles from the nearest roads, a local road in the Sunlight Basin and U. S. route 20 in the North Fork Valley.

The ore deposits occur as narrow fissure veins in Tertiary volcanic breccias, associated with a volcanic and intrusive center. The mineralization is typical, in kind and structure, of most epithermal deposits. This report describes their occurrence, mineralogy, paragenesis, and zoning. The various deposits exhibit a well-exposed vertical zoning and it is principally for this reason that the region is here being discussed.

Ore was first discovered in the Sunlight region about 1893. During the next few years only about 25 tons of high grade ore was extracted. Between 1908 and 1911, a stock company began development at Winona on Sulphur Creek, and is reported to have spent approximately $200,000, without producing any ore. They ceased operations in 1911. In the past 25 years, the region has been deserted except for roving prospectors who have occasionally packed out a ton or two of ore. The total production of the region to date, therefore, is not over 30 tons of ore, valued at perhaps $3,000.

These ore deposits have never before been studied or described,

though their presence was mentioned by Arnold Hague [1] in 1899. The geology was mapped in a reconnaisance manner at that time but the presence of a volcano in the region was not recognized. This paper, therefore, represents the first detailed work done in the Sunlight region, and is the result of four weeks of field work during the summers of 1934 and 1935. Only the surface outcrops could be studied as entry into the abandoned tunnels was unsafe. Consequently, many of the ore specimens studied and assayed came of necessity from the mine dumps. Vertical areal photographs, taken by the United States Forest Service, were used in the field to make the accompanying geologic map.

Acknowledgments.—The writer acknowledges financial assistance received from Princeton University both in the field and laboratory work. The constructive criticism of Professors Edward Sampson and A. F. Buddington was greatly appreciated. The writer thanks Raymond B. Koehler and Donald G. Herring, Jr., for their field assistance and is greatful for the courtesies shown by all who were met in the field. The writer is much endebted to Mr. John V. N. Dorr for the assays given in this paper.

GENERAL GEOLOGIC SETTING.

Physiographic Features.—The area in which the Sunlight mining region is situated is in a rugged part of the Absaroka Range. The district is a complex mass of jagged peaks and horns connected by long, sharp ridges with steep escarpments and well-defined cirques and has a relief of 4,000 to 5,000 feet. The highest point in the area is Sunlight Peak, 11,977 feet. The region has been extensively glaciated and a few small glaciers still exist today. Most of the ore deposits occur above timber line. Fig. 1 presents a general impression of the topography of this region.

General Geology.[2]—All the rocks in this region are extrusive

[1] Hague, Arnold: Absaroka folio. U. S. Geol. Surv. Geol. Atlas, Folio No. 52. 1899.

[2] For a detailed description and discussion of the general geology of this region see: Parsons, W. H.: The geology and ore deposits of the Sunlight area, Park County, Wyoming. Typewritten copy of Doctor's thesis deposited in the library of Princeton University, 1936. Parsons, W. H.: Forthcoming article on the volcanic centers and petrology of the Sunlight area to appear elsewhere.

and intrusive Tertiary volcanics such as are typical of the entire Absaroka Range. Almost all the extrusives belong to Hague's [3] Early Basic Breccia Series of pyroclastics and interbedded flows. This series has a thickness of 5,000 feet in this area, far above its average thickness in the Absarokas as a whole. These extrusive rocks are generally considered to be Miocene [4] in age. The ore deposits are related to a group of intrusives forming the Sunlight Volcano or volcanic center. This volcano must have had a diameter of four or five miles and stood at least 2,000 or 3,000 feet above the present mountain tops.

FIG. 1. A general view of the glaciated topography of the Sunlight mining region with Sulphur Creek Valley on the left and Stinkingwater Peak in the right background. Most of the ore deposits are on or beyond the mountains in the right half of the photograph.

The Early Basic Breccia Series contains andesitic volcanic breccias made up of angular to sub-angular fragments an inch or two in diameter with a matrix of volcanic ash. The common minerals in the fragments and matrix are andesine and labradorite feldspar, augite, green hornblende, and magnetite. The breccias

[3] Hague, Arnold: *Op. cit.*

[4] Rouse, J. T.: The physiography and glacial geology of the Valley region. Wyoming. Jour. Geol., vol. 42, p. 740, 1934.

in the mining region exhibit a great variety of colors, from light gray through rusty yellow and purple to dark brown, due to wall rock alterations. The series is poorly bedded except near two basic plugs where the beds dip outward in all directions exhibiting cone structure. In these actual cones are interbedded light gray to purple-colored tuffs and well-jointed andesitic lava flows.

Just outside the mining region, several small remnants of the Early Basalt Sheets occur on the tops of high peaks. This series consists of many thin, flat-lying basalt and olivine-basalt flows as described in other parts of the Absarokas.[5] There is no indication that any of these flows came from the Sunlight volcanic center, but rather that the Sunlight Volcano stood up as an island around which the basalts flowed from fissures elsewhere.

The intrusive rocks related to the volcanic center of the mining region are dikes, cone sheets, plugs, and a small stock. Their outcrop patterns and sizes may be seen on the accompanying geologic map (Fig. 2). A few thousand vertical dikes, averaging four to ten feet wide, radiate from this center for five to ten miles in all directions. A much smaller number of cone sheets of similar size and composition closely surround the region on three sides. The two main plugs are composed of basalt porphyry, some of it an intrusive breccia. Two coarse-grained bodies, a small stock and a thick ring dike, consist essentially of diorite and syenite.

OCCURRENCE OF THE ORE DEPOSITS.

The important ore deposits, carrying gold and silver, are close to, but generally not in, the ring dike, stock, and basaltic plugs. Comparatively few rich veins occur as close as a few hundred feet to the large stock. The deposits in or near the stock contain only quartz and pyrite. The veins more than about one half mile from the intrusives are small, insignificant, and few in number. The important veins occur in fault zones, shear zones, or at the contacts of dikes or, rarely, larger intrusive bodies. Where the

[5] Rouse, J. T.: Volcanic rocks of the Valley area, Wyoming. Trans. Am. Geophy. Union, 16th Ann. Meet., pp. 279–284, 1935.

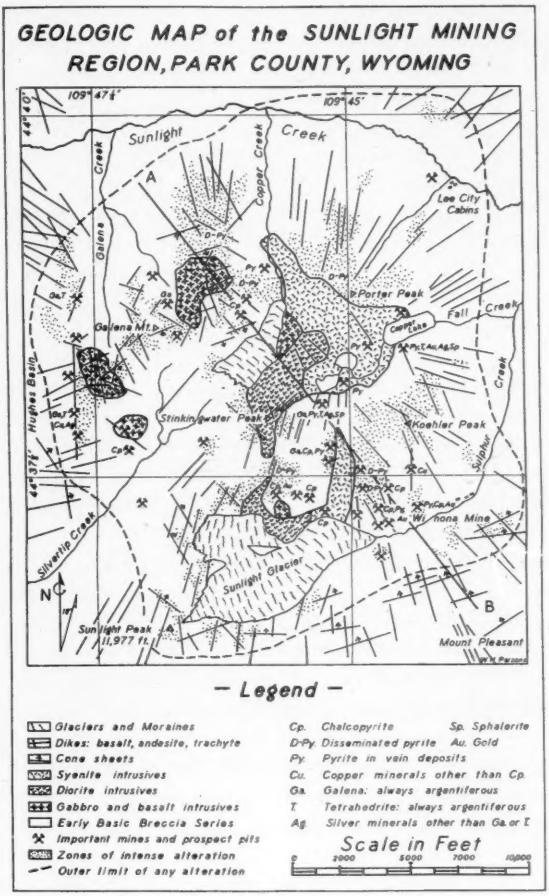


FIG. 2.

veins occur at contacts with dikes or stocks, a shear zone is generally present. In short, therefore, the ore deposits occur in fault or shear zones developed in the volcanic breccias and less commonly in the intrusive rocks.

A relatively small number of mineralized faults have been recognized in the volcanic breccias, but these few carry some of the best ore veins of the area. Some faults have a wide, coarsely-brecciated zone that has been impregnated by the mineralizing solutions. Other faults carry ore veins in a fine-grained gouge.

The majority of the veins of this region occur in weak shear zones where minor movement has fissured the ground sufficiently to permit entrance of ore solutions. The ore minerals may occur in fissure veins, in irregular deposits in the broken ground, or as thin films on joint planes near the shear zones. These shear zone veins occur in the volcanic breccias, at dike contacts, and in the larger intrusive bodies.

Fissuring and Fracturing.—An early period of fissuring and fracturing occurred during volcanic activity and intrusion. At that time, radial cracks were formed by upward and outward pressures due to volcanic explosions and the force of intrusion. These cracks were filled by magma forming the radial dike system. It is believed that the fissures of this period were of no value as channels for the ascending ore solutions.

Some time after the last dike intrusion, further, but much less extensive, fissuring took place. This was probably caused by settling, contraction, and other processes of adjustment of the vast amount of extrusive and intrusive material emplaced by the activity of the Sunlight Volcano. These later fissures and shear zones formed irregularly in the volcanic breccias and intrusives, in places reopening old faults or old dike-filled fractures. It is apparent that these fissures formed the channels for the mineralizing solutions and determined the location of mineral deposition. There is no evidence of any post-mineralization fracturing.

STRUCTURE OF THE VEINS.

The ore deposits occur in two different types; the stringer and the brecciated types. Both of these exhibit the typical banded, crustiform, and vuggy characters of near-surface veins where solutions have filled open fissures and cavities. In the stringer type of vein the minerals occur in banded veinlets that parallel

the shear or fault zone. In the brecciated type of vein, the mineralization has surrounded fragments of wall rock in fault zones and banding occurs around each fragment.

The veins of this region are all narrow, averaging but a few inches to half a foot wide. The brecciated type of veins are a few feet wide, but these are copper-bearing only. The gold and silver-bearing veins are all narrow. The veins commonly occur singly and not in systems, and are very pockety, being characterized by pinches and swells. A vein may carry good ore for a hundred feet or so and then become nearly barren with only gangue minerals continuing. Being narrow, scattered, and lenticular in structure the veins do not warrant any large scale mining activity.

MINERALOGY.

The ores are base-metal type with occasional good silver and rare gold content. Chalcopyrite, pyrite, and galena are the only common minerals seen in the hand specimen; others occur either in minute quantity or are restricted to one or two veins. Examination with the microscope shows tetrahedrite to be widespread in the district.

Pyrite is one of the commonest metallic minerals of the region occurring in all veins and being abundant in about one fourth of them. It occurs in irregular and corroded grains or masses, though it is commonly well crystallized in cubes, octahedrons, and, more rarely, pyritohedrons.

Chalcopyrite is the commonest ore mineral in the Sunlight mining region. It occurs in most veins and is dominant in over half of them, in some being the only metallic mineral. It is found in coarse crystalline masses, rarely as good tetrahedrons, or in minute specks and streaks in other minerals.

Galena occurs in about half of the deposits, dominating in a few. It is in all cases silver-bearing and associated with carbonates.

Tetrahedrite is present in many veins in chalcopyrite and galena, but it is abundant nowhere. It is the most important silver ore mineral of the district.

Sphalerite is surprisingly scarce, occurring in only a few veins as rare greenish-yellow grains, nowhere associated or mixed with galena.

The *gold* of the region occurs in minute specks of native gold and as sylvanite in tiny veinlets. The latter mineral was positively identified, and may be seen in Fig. 3. Both gold minerals are associated with chalcopyrite.

Bornite and *famatinite* (or enargite) occur in rare small grains in two or three deposits. Bornite occurs abundantly in one vein intergrown graphically with chalcocite as shown in Fig. 4. The chalcocite occurs in coarse blue crystalline areas with orthorhombic cleavage. The coarse crystallization together with the graphic intergrowths with bornite suggests a hypogene origin for the chalcocite.

Wolframite, proustite, stromeyerite, and *bournonite* have been noted each from but a single vein and each occurring without the others. The first two are fairly important in their respective deposits. The wolframite occurs in one eighth to one four inch striated prismatic crystals.

Magnetite is found in the area but not actually in the fissure veins. It occurs in small pegmatitic veins associated with the intrusive rocks.

FIG. 3. Sylvanite veinlets (white) cutting chalcopyrite (background) with small areas of tetrahedrite (light gray) and calcite (dark gray). ×77.

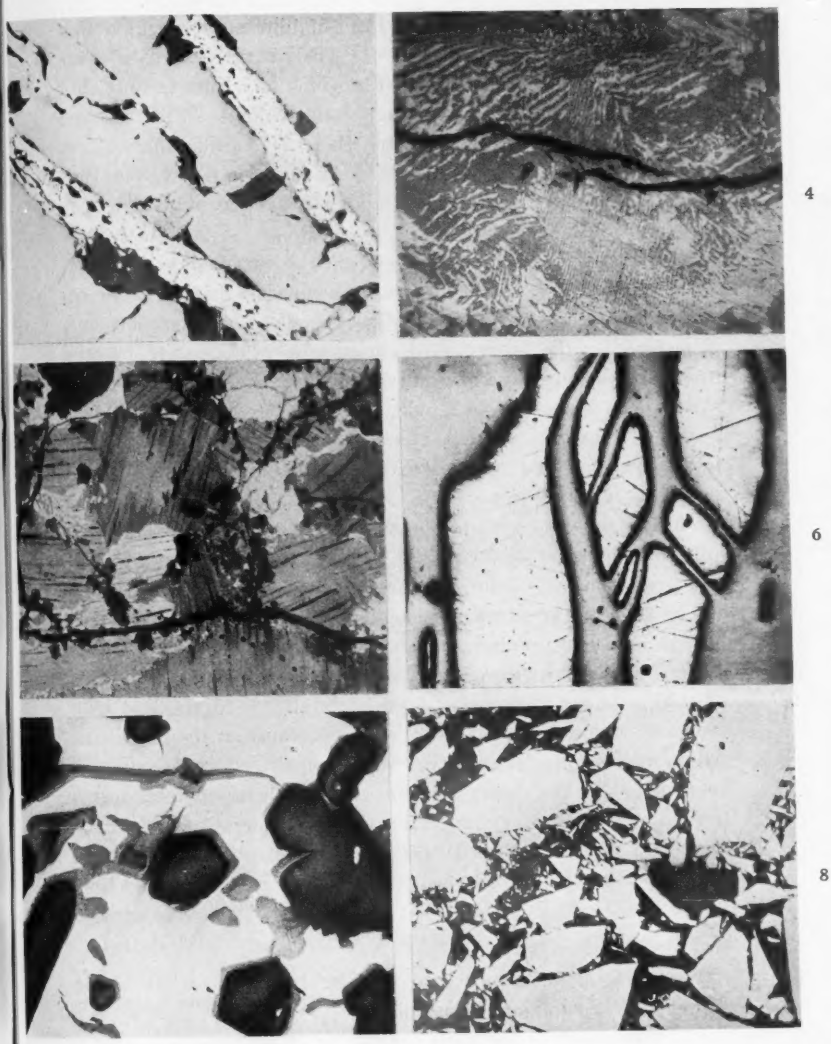
FIG. 4. Graphic intergrowths of bornite (white) and chalcocite (gray). The irregular black vein is copper pitch. ×600.

FIG. 5. Coarse grained chalcocite (light gray) showing orthorhombic cleavage and alteration to covellite (darker gray). Very dark veins are copper pitch and very dark blotchy areas are normal fine-grained covellite. White areas are bornite. ×124.

FIG. 6. Pyrite (lighter areas) veined, replaced, and surrounded by chalcopyrite. ×128.

FIG. 7. Euhedral quartz crystals (very dark gray) in chalcopyrite (white) with replacement veins of limonite (light gray). ×77.

FIG. 8. Brecciated chalcopyrite (white) surrounded by calcite (gray). ×128.



FIGS. 3–8.

The characteristic gangue of the Sunlight mining region is a well-banded quartz-carbonate one. The quartz occurs to some extent in every vein whereas a few veins have quartz only, but carbonates have a much greater total volume. Siderite and ankerite are commonest, although there is considerable calcite. Small crystals of adularia are found sparingly in a few veins and milky-white, platy barite is an important gangue mineral in one fault zone.

Secondary Minerals.—Supergene enrichment is not very noticeable in this area. The few supergene minerals that do occur result mostly from weathering. Erosion, due to the great relief, is faster than the processes of enrichment. "Limonite" is the most conspicuous mineral occurring as yellowish, brownish, and blackish surface stains over wide areas and as thin gossans over pyrite or chalcopyrite-rich veins. Malachite and azurite are found sparingly as surface coatings. Microscopic examination reveals a few tiny veinlets of supergene minerals in apparently fresh hypogene ore minerals. Of these limonite and copper pitch are most abundant, and covellite, anglesite, cerussite, cerargyrite, and sooty chalcocite occur in traces.

The supposed hypogene chalcocite is about one fourth replaced by covellite in a peculiar fashion. Fine-grained covellite comes in along cracks in a normal replacement manner. But large grains of chalcocite are also almost completely altered to covellite with the preservation of the structure and appearance of the chalcocite. All gradations are seen between pure unaltered chalcocite and covellite. The one fades into the other with no contact, just a transition zone that has properties of both minerals, the color of chalcocite with weak covellite that is red in polarized light—a diffusion contact (Fig. 5).

PARAGENESIS

The paragenetic sequence of the ore minerals of the whole region may be summarized as follows:

1. Pyrite, start of the early quartz.
2. Continued quartz, adularia.

3. Wolframite, sphalerite, last of the early quartz.
4. Chalcopyrite, bornite, and chalcocite.
5. Tetrahedrite, famatinite, bournonite, stromeyerite.
6. Sylvanite, native gold.
7. Galena, start of the carbonates.
8. Proustite, followed by a little late chalcopyrite.
9. Most of the carbonates, late quartz.

Pyrite is always unquestionably the earliest metallic mineral. It is replaced and cut by most other minerals, particularly chalcopyrite (Fig. 6).

Quartz is also early but it veins pyrite, so that some if not most of the early quartz came in after some of the pyrite. Quartz also veins sphalerite and replaces euhedral wolframite. It is believed, therefore, that the early generation of quartz came mainly after pyrite and continued until after some of the sphalerite. Euhedral quartz is seen in many copper ores (Fig. 7), where six-sided crystals are surrounded by chalcopyrite, bornite, or tetrahedrite showing that the quartz is earlier than the chalcopyrite stage. In the quartz-pyrite veins there is a later, more chalcedonic, milky quartz, which is probably later than all the hypogene minerals. Some later quartz is seen in other deposits cutting galena in fine veinlets. Two generations of quartz, therefore, seem established.

Adularia occurs in good euhedral crystals projecting from the vein walls into chalcopyrite and is, therefore, earlier than the chalcopyrite.

Tiny veinlets of chalcopyrite in bornite might be ex-solution chalcopyrite or possibly supergene chalcopyrite. However, coarse grains of chalcopyrite and bornite occur more or less intergrown suggesting that the two minerals are of the same age. The hypogene chalcocite, occurring intergrown with the bornite as it does, belongs here also.

Tetrahedrite veins chalcopyrite in many deposits and forms rims around chalcopyrite and bornite in others, and also appears to be the same age as chalcopyrite. This is also true of famatinite, bournonite, and stromeyerite. It is believed that these minerals are almost the same age as chalcopyrite in the silver

veins, but considerably younger in the copper veins. Sylvanite and native gold may belong in this group but veins of sylvanite in chalcopyrite seem to be a little younger than tetrahedrite.

Galena is found in definite veinlets that cut chalcopyrite, and some irregular areas of chalcopyrite and tetrahedrite are commonly completely surrounded, engulfed, and corroded by large areas of galena. Galena is considered, therefore, the latest hypogene ore mineral, except in one deposit. There, proustite replaces galena and in turn has its edges replaced by small amounts of chalcopyrite. This latter would seem to be a second generation of chalcopyrite.

Most of the carbonate gangue is later than the metallic minerals although its precipitation commenced during the galena stage. At the Winona Mine, chalcopyrite and tetrahedrite are in places minutely brecciated and the cracks are filled with calcite (Fig. 8). Such brecciated areas are rarely veined by unbrecciated galena, which is, therefore, later than the brecciation and calcite. Consequently, some of the calcite was deposited before some of the galena. Within the carbonates themselves, the sequence is siderite, ankerite, calcite indicating that the last solutions were lowest in iron.

This Sunlight paragenetic sequence is similar to other sequences. At Cooke City, Montana,[6] twenty miles distant, the paragenesis is as follows: (1) quartz, (2) pyrite, (3) chalcopyrite, (4) small amounts of sphalerite, (5) galena and tetrahedrite, (6) sphalerite, (7) ankerite and small amounts of quartz. The Cooke City mineralization is similar to the Sunlight except that zinc is abundant in the former and almost absent in the latter district.

WALL ROCK ALTERATION.

The rocks in the Sunlight mining region have been considerably effected by hydrothermal solutions. Most of the rocks within the line marking the outer limit of alteration on the accompanying geologic map are altered to at least a small extent. There are

[6] Lovering, T. S.: The New World or Cooke City mining district, Montana. U. S. Geol. Surv. Bull. 811–A, p. 55, 1929.

several areas of more intense alteration also shown on the map. The wall rocks of the veins display considerable alteration over the region as a whole, however, the amount of alteration has not been extensive, but is rather modest and in keeping with the narrowness of the veins. The minerals that have been found in the country rock are the following, approximately in the order of their abundance: common; chlorite, calcite, sericite, kaolin, and pyrite, and less common; limonite, epidote, quartz, and zeolites. These occur in various combinations but the most important types of alteration are propylitization, sericitization, and carbonatization. The alterations occur in almost every kind of rock, though the large syenite stock is practically unaltered.

The most widespread and persistant type of alteration that occurs in almost all of the rocks of the region is rather weak and generally affects only the mafic minerals. The latter are altered to chlorite with varying amounts of calcite and a little epidote and pyrite is generally present in small amounts. Where the alteration becomes more intense, sericite appears in the feldspars and chlorite spreads to the groundmass. This type of alteration, characterized by chlorite with minor calcite and pyrite, is what is here called propylitization.

The large areas of more intense alteration occur near the larger intrusive bodies or over areas where the stock has flared out in depth. These are areas of disseminated pyrite with a trace of copper, and calcite, sericite, and kaolin are also abundant. Here the rocks are bleached and greatly iron-stained on joint planes and weathered surfaces giving rise to areas of light color that are much streaked and stained with yellows and browns. Some of these bleached pyritic areas contain principally sericite. In others, calcite is as common as sericite, and in still others the carbonate predominates. Generally, some kaolin is also present and considerable late "limonite."

The alterations localized to the actual walls of the ore veins are very similar to the widespread alterations just described, but are more pronounced or intense. The zeolites heulandite and chaba-

zite occur in pockets in the volcanic breccia wall rock of one vein. Silicification occurs sparingly in a few vein walls.

In the vicinity of some veins the type of alteration varies outward from the veins, one type being superimposed on the other. By studying these occurrences it has been possible to work out the following sequence of wall rock alteration in the Sunlight mining region: (1) widespread alteration of mafic minerals to chlorite and pyrite, more intense near fault and shear zones. Possibly some calcite formed at this time; (2) less extensive but more intensive alteration to sericite of the feldspars and earlier formed chlorite. Probably some kaolin formed at this time; (3) deposition of the ore minerals with, rarely, some silicification in the immediate walls. More pyrite was added at this time close to the veins; (4) carbonatization of the wall rocks, probably beginning during stage three. These four stages are genetically connected to the ascent of the ore solutions. At a much later time, a considerable amount of the kaolin and possibly some of the calcite was deposited by ground water solutions.

CLASSIFICATION OF THE DEPOSITS.

The veins of this region are here divided into seven classes according to mineral assemblages. These classes might be put into two groups according to the temperature of formation but they grade into one another so that the dividing line is rather arbitrary. The classification is as follows:

I. Medium temperature veins.
   1. Quartz-pyrite deposits.
   2. Complex gold-silver-tungsten deposit.
   3. Chalcopyrite-pyrite-gold veins.

II. Low temperature veins.
   4. Copper ores, mainly chalcopyrite veins.
   5. Argentiferous-galena veins.
   6. Complex silver veins.
   7. Barren carbonate veins.

A few assays have been made of the ores of the region and are given in the accompanying table. In most cases these repre-

sent an average of ore found on the dump, but in a few cases the assay was made from average samples of the ore.

TABLE I.

ASSAYS OF THE ORES OF THE SUNLIGHT MINING REGION.[7]

(Classification and name of claims)	Au. oz. per ton	Ag. oz. per ton	Copper %	Lead %
QUARTZ-PYRITE VEINS				
Average of two deposits	0.03			
COMPLEX AU-AG-W DEPOSIT				
Near lower Copper Lake	0.54	13.46		
CHALCOPYRITE-PYRITE-AU VEINS				
* Big Goose Claim	0.82	trace		
Winona Mine	0.58	0.88		
CHALCOPYRITE VEINS				
Copper King Claim	0.04	0.62	3.35	
Silvertip Claim	0.06	4.62	3.85	
* Butte Claim	0.22	3.14	4.43	
ARGENTIFEROUS-GALENA VEINS				
Hoodoo Claim	0.02	1.58	trace	9.40
* Hardee's Claim	0.04	20.24	trace	62.23
COMPLEX SILVER VEINS				
Tip Top Claim	0.02	7.14	trace	0.60
* Evening Star Claim	0.02	91.44	1.40	1.30
Novelty Claim	0.06	19.00	0.75	13.10
BARREN CARBONATE VEINS				
* Morning Star Claim	0.01	0.23		

* Assay sample taken from ore vein outcrop.

The other assay samples are averages of the ore found on the dumps.

All these assays probably indicate the relative order of magnitude but the figures are not accurate enough for commercial use.

Quartz-Pyrite Deposits.—Veins carrying only quartz and pyrite occur in or very close to the actual stock. They carry no gold or copper and are consequently of no economic value. The veins are characterized by vugs and crustification of the quartz with noticeable limonitic stains. The wall rocks are weakly propylitized with

[7] Assays made by Charles O. Parker & Co., Denver, Colorado, October 1935 and February 1936, through the courtesy of Mr. John V. N. Dorr, president of the Dorr Co.

some epidote and silica. These are the highest temperature vein deposits in the region.

Complex Gold-Silver-Tungsten Deposit.—There is one very unusual vein which is classed by itself. It occurs in a shear zone in volcanic breccia near the contact of the stock. It carries considerable gold and silver and its common minerals are pyrite, wolframite, and tetrahedrite with some sphalerite, rare chalcopyrite, and bournonite. The gangue is entirely quartzose and the wall rock carries much pyrite.

Chalcopyrite-Pyrite-Gold Veins.—Some veins found on the north side of Sulphur Creek are among the more promising in the region. It is here, at Winona, that considerable mining equipment was set up in 1910. Ore in this class of deposits occurs in shear zones at dike contacts in the volcanic breccias. The ores consist essentially of chalcopyrite and pyrite in a 50–50 ratio. Small microscopic amounts of tetrahedrite, galena, and very rarely sphalerite are associated with the chalcopyrite. The gold occurs as sylvanite with rare native grains in veinlets in the chalcopyrite. The chief gangue mineral is quartz with small amounts of calcite and adularia and typical propylitization in the wall rocks.

Copper Ores: Mainly Chalcopyrite Veins.—Here are classed some fairly good copper-bearing veins up to ten feet in width which carry chalcopyrite as the chief metallic mineral or, rarely, chalcocite and bornite. These chalcopyrite veins occur in shear and fault zones in the volcanic breccias. Besides chalcopyrite, traces of tetrahedrite, famatinite, bornite, and galena are present in most veins with low silver values. The gangue is a mixture of quartz and carbonates in about equal proportions.

Argentiferous-Galena Veins.—Veins of almost identical occrence to the last group but carrying only coarse galena belong here. This galena is argentiferous, but no tetrahedrite or other silver minerals are present. Sphalerite is generally lacking and chalcopyrite and pyrite are scarce. In the gangue, iron carbonates dominate over quartz and sericite; calcite and pyrite make up the secondary wall rock minerals.

Complex Silver Veins.—The veins that carry high silver values and have various silver-bearing minerals in addition to galena are put in this class. The majority of them occur near one of the basaltic explosion plugs in fault and shear zones in the volcanic breccias. Galena and argentiferous-tetrahedrite are the commonest minerals but various other silver minerals occur, including proustite and stromeyerite. There is always a small amount of chalcopyrite and in most veins also pyrite. The main gangue is a carbonate one with calcite, ankerite, and siderite although barite is also important. The chief wall rock alteration is sericitization generally with important amounts of kaolin.

Barren Carbonate Veins.—In places, where the ore pinches out, only the gangue minerals remain in the extension of the veins. This is particularly true of the silver ores with their carbonate gangues. The veins that carry almost no metallic minerals are classed as barren carbonate veins. They have about the same occurrence as the two previous classes. They carry rare specks of galena in calcite, ankerite, and siderite with small amounts of quartz. They are the lowest temperature hydrothermal deposits in the region.

ZONING.

Zoning is evident in the Sunlight ore deposits above and around the intrusive bodies. Gold occurs in the deeper and central zone, copper farther out and up, and silver farthest out and especially up. This zoning is most important vertically and for this reason and due to the 2,000 to 3,000 foot relief, the zoning is not expressed in the areal distribution of the deposits as seen on the accompanying geologic map of the Sunlight mining region. An attempt has been made, however, to show the general outline of the vertical zones on the geologic cross section of this map (Fig. 9).

The zones depended on the temperatures of the mineralizing solutions. At the time of ore formation the region was at the base of the Sunlight Volcano where the temperatures were relatively high and the temperature gradients were steep. These

temperature changes were much greater in a vertical than in a horizontal range within the area now mineralized. There was some centering of the temperature zones around each volcanic conduit and stock but these were more or less merged into one large scale centering around and over the whole area of intrusive activity, so that the only zoning of the ore veins that is really noticeable today is a vertical one. We might think of the whole area within the limits of alteration as shown on the geologic map as the throat of a composite volcano similar to the Cripple

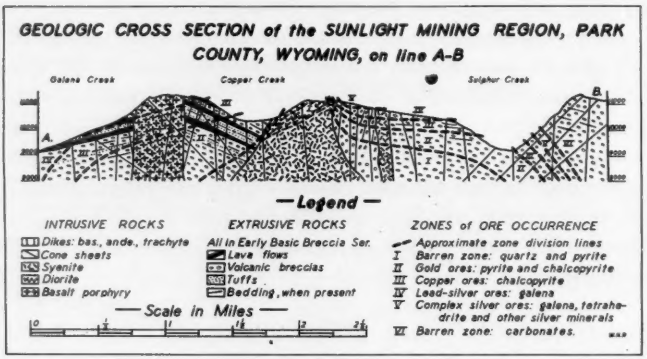


FIG. 9.

Creek volcano.[8] As mineralizing solutions rose through this area, similar mineral assemblages were deposited at about the same elevations throughout the district because the different temperature zones occurred as horizontal planes.

A complete zoning cannot be seen in any one vein because not enough of the vein is exposed. The zoning has been worked out by taking into account the slight changes in each exposed vein, their overlaps, and their relative positions. By this means, an

[8] Loughlin, C. F.: Cripple Creek mining district. Internat. Geol. Congress Guidebook No. 19, pp. 113–122, 1932. Loughlin, C. F., and Koschmann, A. H.: Geology and ore deposits of the Cripple Creek district, Colorado. Colo. Sci. Soc. Proc., vol. 13, no. 6, pp. 217–435, 1935.

ideal composite zoned vein may be drawn up which runs through the entire classification of the vein deposits from quartz-pyrite at the bottom to barren carbonate at the top. More in detail, such a vein carries quartz and pyrite in its deepest zone in the intrusive rock. Farther up in the volcanic breccias, chalcopyrite and gold appear, then as chalcopyrite becomes more abundant pyrite and gold decrease in amount till the vein carries only copper. At this point carbonate becomes as important as quartz. Farther up still, galena comes in and takes the place of the chalcopyrite. The silver content increases upward and various silver minerals appear as the lead content lessens and quartz becomes rare. Finally, at the top all of the ore minerals disappear and the vein carries only carbonates.

Many examples of this zoning might be cited. On the western side of the district are the Silvertip and Evening Star claims occurring about 2,000 feet apart horizontally and each about equally near a basaltic plug. The former, however, is 1,000 feet below the latter vertically and is a chalcopyrite vein whereas the Evening Star is a complex silver vein. The author believes that if one were to follow the Evening Star lode down 1,000 to 1,500 feet its silver content would decrease greatly and copper would be the main metal present.

Again, on the north side of Sulphur Creek running up towards Stinkingwater Peak is clear evidence of this vertical zoning. At 9,500 feet near Sulphur Creek are the gold-bearing veins of the Winona mine, at 10,000 feet are several chalcopyrite veins, at 10,500 feet is an argentiferous-galena vein, and at 11,000 feet a complex silver vein occurs. The vertical position of the various veins on this slope is perfect for the vertical zoning here outlined, but the lead and silver bodies are nearer the intrusive masses than the other veins. It is for these reasons that the author believes vertical temperature gradients were far more important in this zoning than the immediate proximity of intrusive bodies.

ORIGIN AND COMPARISON WITH OTHER DISTRICTS.

The ore deposits of this region fall in the epithermal and a few, perhaps, in the leptothermal divisions of Lindgren and Graton. The low temperature veins of this region are typical of the base-metal deposits of the epithermal veins, and the medium temperature veins may be classed with the leptothermal deposits as they formed at shallower depths than true mesothermal veins. All the vein deposits have banded, crustiform, and vuggy structures, which are indicative of formation at shallow depth. There can be no doubt of the magmatic source of these hydrothermal ore veins. Their nearness to and arrangement around and in the stock and plugs of the Sunlight Volcano is proof of a genetic connection with the intrusives. The ores were formed after intrusion of the stock and dikes as the last phase of volcanic activity.

The medium temperature veins occur today between 9,500 and 10,000 feet and the low temperature veins are all above 10,000 feet. The highest mountains in the region are almost 12,000 feet high. Consequently, the medium temperature veins must have formed at a depth of at least 2,000 to 3,000 feet. There is no basis of exact measurement of how much more material was once piled above this region: that is, of the former height of the Sunlight Volcano. It seems likely, however, that a minimum of some 2,000 feet of additional volcanic material has been completely eroded. It may be concluded, therefore, that the low temperature veins were formed at approximate depths of 3,000 to 4,000 feet and the medium temperature veins at 4,000 to 5,000 feet.

There are many other regions where epithermal ore veins similar to those in the Sunlight region are found in volcanic rocks. Among these, as summarized by Lindgren,[9] are the following, which carry mainly gold but are otherwise similar to the Sunlight: Transylvania and Hungary where gold-bearing veins occur in extrusive andesites; Thames and Waihi Districts, New Zealand where andesite and dacite flows are richly mineralized; and the

[9] Lindgren, Waldemar: Mineral deposits, pp. 450, 543. 1933.

Black Mountains of Arizona where gold veins occur in volcanic andesites. At Cripple Creek, Colorado,[10] although the mineralization is quite different, the location of the ore in the roots of a volcano resembles the location of the Sunlight ore. At Cooke City, Montana,[11] a similar and, in fact, related mineralization occurs, although in Paleozoic rocks. The San Juan region[12] in Colorado, however, is most like the Sunlight both as to occurrence and actual ore minerals present.

The Cooke City ores occur principally in Paleozoic limestones and are generally higher temperature deposits than the Sunlight ores. They occur as contact metamorphic and replacement deposits as well as fissure veins. The mineralization, other than in the contact metamorphic deposits, however, is very similar, consisting essentially of quartz, pyrite, chalcopyrite, galena, sphalerite, tetrahedrite, ruby silvers, and ankerite. This mineralization is associated with a monzonitic intrusive of about the same age as the similar Sunlight intrusives. The Cooke City district is only about twenty miles north of the Sunlight. The magmas of these two regions belong to the same petrogenetic province and the ore deposits of the two regions form one metallogenetic province. At Sunlight, the mineralization is up in the volcanic breccias and at Cooke City it is deeper down in the underlying limestones.

The San Juan region contains many mining camps, all of similar nature, with the ore deposits occurring in volcanic tuffs and breccias. The ores of each mining camp are located around large stocks, and the many areas of small mining activity and prospecting are located around smaller stocks and volcanic centers. The Sunlight is similar to one of these smaller prospecting areas. The mineralogy and wall rock alterations of the Sunlight area are similar to, though perhaps simpler than those of the San Juan. Also in the San Juan, large bodies of volcanic rock are more or

[10] Loughlin, C. F., and Koschmann, A. H.: *Op. cit.*

[11] Lovering, T. S.: *Op. cit.*

[12] Cross, Whitman, and Larsen, E. S.: A brief review of the geology of the San Juan region of southwestern Colorado. U. S. Geol. Surv. Bull. 843, 1935.

less altered near the stocks to a light gray-white or iron-stained rock made up of kaolin, sericite, and abundant pyrite. These areas must be very similar to the areas of intense alteration near certain of the Sunlight intrusives. The Sunlight region might well be considered a very small scale reproduction of the San Juan.

HAMILTON COLLEGE,
CLINTON, NEW YORK,
May 5, 1937.

DISCUSSION AND COMMUNICATIONS

HYDROTHERMAL LEACHING OF IRON ORES.

Sir.—In an article entitled "Hydrothermal Leaching of Iron Ores of the Lake Superior Type—a Modified Theory," [1] which appears in a recent number of ECONOMIC GEOLOGY, Professor Gruner makes the following statement:

> . . . intrusive activity immediately preceded the formation of ore bodies and as far as known lasted until after the ore bodies were completed. This applies especially to the Gogebic and Marquette ranges. One does not receive that impression for the Marquette range, however, when reading the guide book of the International Geological Congress (Guidebook 27, Lake Superior Region, 1933, p. 16). C. O. Swanson does not mention there the earlier intrusives, which arrived before upper Huronian time in the Negaunee iron formation according to Van Hise, Bailey and Leith. The writer thinks them responsible for the hard ores, that is the heat which came from the larger masses of the same magma. The soft ores were formed by the heat from the Keweenawan magmas. This statement is a departure from his earlier ideas . . . that all the Marquette ores might have been of one period of concentration.

The writer does not intend to give a general criticism of Gruner's hypothesis, as the main objections to it have already been ably presented by Leith, Royce, and others. However, the above quotation seems to be quite misleading in several respects, and the writer wishes to make clear his own position as well as to give the general reader a better perspective on the main facts concerning the relations between ore formation and igneous activity on the Marquette range.

In Guidebook 27 the writer did not mention the occurrence of intrusives of middle Huronian age because he believes that, if present at all, they are a negligible quantity. The question of the age of the abundant basic intrusives in the Huronian was given considerable attention at the time of mapping portions of

[1] Gruner, J. W.: Hydrothermal leaching of iron ores of the Lake Superior type—a modified theory. ECON. GEOL., vol. 32, no. 2, p. 129, 1937.

the Marquette range a few years before the guidebook was written, and it was concluded that practically all of these intrusives belong to the upper Huronian and Keweenawan.

Gruner gives Van Hise, Bayley, and Leith as authorities for the statement that there are earlier intrusives which I did not mention in Guidebook 27. Apparently Gruner is referring to Monographs 28 and 52 of the U. S. Geological Survey. Yet in Monograph 52, on page 268, the following statement appears: "Much the larger number of intrusive masses are distinctly of post-Huronian and probably Keweenawan age." It is true that some of the earlier reports tentatively assigned certain large intrusive masses to the middle Huronian (as it is now called), and also included in the Negaunee formation certain volcanics near Clarksburg, but it is equally true that these conclusions have been modified in the latest reports. In the latest publication, Professional Paper 184, no basic intrusives or volcanics (greenstones) are listed in the middle Huronian of the Marquette range on the correlation chart facing page 10. In short, the writer believes that Gruner's statement about the presence of middle Huronian intrusives on the Marquette range is quite misleading in the light of present knowledge concerning the geology of this range.

It is, of course, well known that some distance to the southwest of the Marquette range the Hemlock volcanics were erupted in middle Huronian time. But it is also to be noted that the hard ore horizon, which Gruner now ascribes to the influence of middle Huronian magmas, becomes less prominent and finally disappears when traced toward the largest display of these eruptives.

It is apparent, therefore, that the presence of hard ore seems in no way associated with that of middle Huronian eruptives. On the other hand, the one outstanding association is that of the hard ore horizon with the base of the Goodrich quartzite, which is the lowest member of the upper Huronian.

Regarding the late pre-Cambrian intrusives and their relation to the formation of soft ores, the main geological relations on the Marquette range are as follows.

In the western part of the range, there are granitic intrusives associated with intense metamorphism of the Huronian series.

including the iron formation and the large basic intrusives. Here the main lower part of the iron formation is a magnetite-grunerite type, apparently due to metamorphism of cherty siderite, or what is commonly called unoxidized iron formation. The upper part, the hard ore horizon, is composed largely of specularite, magnetite, and quartz, and has apparently developed from the metamorphism of iron formation that was oxidized and partly leached to ferric oxides and chert during the interval between middle and upper Huronian time. It is clear that the lower main part of the iron formation was unoxidized at the time of deformation, granitic intrusion and metamorphism. It is also evident that these processes affected the large basic intrusives in the Huronian. Finally, the present character of the soft ores and associated ferruginous cherts confirms the deduction that the oxidation and leaching of the iron formation forming these came after the period of deformation and metamorphism. Obviously the eruption of the large basic intrusives and the formation of soft ore were separated by a long interval of time.

The large masses of basic intrusives that occur in the Marquette range are therefore eliminated as possible sources for the hydrothermal solutions required by Gruner's hypothesis. There remain, however, two other possible sources. One of these is the granite intrusives, but that they have caused the formation of the soft ore is so completely at variance with the field relations that apparently no one has entertained this hypothesis. The other source is the few dikes of fresh diabase that cut the granite and other rocks of the range. As far as the writer knows, there is nothing in the geological history that makes it impossible for the magma that was the parent of these dikes to have furnished heat and solutions at the time when the soft ores were formed, but the general reader should realize that the visible display of this magma consists only of a few dikes, and not the large masses of basic intrusives that are prominent on the maps and geologic sections of the range.

C. O. SWANSON.

DEPT. OF GEOLOGY,
UNIVERSITY OF BRITISH COLUMBIA,
June 9, 1937.

REVIEWS

Geology of the Silver City District and the Southern Portion of the Comstock Lode, Nev. By VINCENT P. GIANELLA. University of Nevada Bull., vol. 30, no. 9, pp. 108, Reno, 1936.

This is the latest in a series of excellent bulletins on the mineral deposits of Nevada that have been published in recent years by the Nevada Bureau of Mines and the Mackay School of Mines. A revision of the geology of an old and classic district is particularly welcome, and it is hoped that the State Bureau of Mines may restudy the geology of other famous camps, such as Eureka, Goldfield, and Austin, as it has done for Tonopah, Comstock, and some other districts of less importance.

This publication, though treating in detail only the southern part of the Comstock Lode area, the Silver City district, presents a complete revision of the geology of the entire Lode and introduces new and interesting concepts. The accompanying geologic map covers only the area immediately surrounding Silver City. A sketch map covering the entire area considered would have added greatly to the value of the bulletin.

The rock sequence as worked out by the author, except for a few minor points, essentially confirms the early work of Becker. The oldest rocks of the area are metamorphosed sediments overlain with angular unconformity by altered lavas. These are older than the intrusive quartz monzonite, which is correlated with the Sierra batholith, and are regarded as probably Triassic, though the sedimentary rocks may be in part Paleozoic. As Eldorado Canyon, not far from the area studied, shows a conformable sequence of Upper Triassic and Lower Jurassic sediments, it would appear that a Lower Jurassic age for the older lavas is also possible.

The oldest Tertiary lavas include andesite and rhyolite, which, on the basis of the similarity of the relations of rhyolite and underlying gravels on both the east and west flanks of the Sierra, are regarded as of Eocene age. Although the evidence offered is not entirely convincing, it at least strongly suggests that the oldest lavas in the Great Basin may date from the Eocene rather than the Miocene. To the reviewer, however, it would seem that an argument could be made for correlating the early lavas of Silver City with the oldest volcanic formations of the Tonopah district, considered to be of Miocene age.

An erosion interval separates the older lavas from the overlying Alta

andesite, a group of lavas, breccias, and tuffs over 3,000 feet thick. The recognition of a sedimentary member, the Sutro tuff, within the Alta andesite is of great importance since it permits a quantitative measurement of the total displacement on the Comstock fault. On the basis of similarity with the Miocene andesites of the Sierras and Cascades, the Alta andesite is regarded as Miocene. Since the publication of this bulletin this correlation has been confirmed by the discovery of Miocene leaves within the Sutro tuff by Johnston and Gianella.

Dikes of andesite porphyry cut the Alta andesite in the Silver City region, but the main mass of intrusive, the Davidson diorite, is outside the mapped area. The convincing proof offered by the author, confirming the determination by D. T. Smith in 1912, that the diorite is intrusive into the Alta andesite, is a major contribution to the geology of the region.

Following the intrusion of the diorite there was faulting, mineralization, and erosion, followed by the eruption of the Kate Peak andesite, which "grades into" lake beds containing lower Pliocene fossils. Later came the development of an erosion surface, regarded as of late Pliocene age, and, after renewed faulting, the eruption of the Knickerbocker andesite. The volcanic history closes with a small flow of Quaternary basalt.

The major structural feature of the area is the Comstock fault, and the work of the author clearly shows a succession of movements, which he divides into two periods: one, "the Comstock period," was largely premineral; the other, "the Davidson period," was post-mineral but "at least as old as late Pliocene," and is expressed by the present topography. Small recent movement along the old faults has resulted in minor displacement of alluvial fans.

The author considers that the prevailing westward dip of the early lavas east of the fault is due to pre-Comstock faulting and tilting rather than to rotation of the downthrown block. The Comstock faulting began after the intrusion of the Davidson diorite, and ended prior to the outflow of the Kate Peak andesite. The amount of displacement during the Comstock period of faulting has been determined to be greater than 2,000 feet at Gold Hill, just north of the area mapped. This amount decreases southward until, a short distance south of Silver City, the estimated displacement is only 500 to 700 feet. The map suggests that a part of this difference may be due to distribution of the displacement along the many branch veins of the Silver City region, and possibly in part along the Occidental vein.

North of the mapped area the displacements of both periods took place within the fault zone but the later movement followed the footwall of the Lode; in the Silver City region, however, the later displacement took place along an unmineralized fault west of the Lode. The amount of this

displacement is indicated by the break in the Pliocene surface, and, according to the author, amounts to about 1,500 feet at Gold Hill. The validity of this measurement depends, of course, on the identity of the surface on the two sides of the fault. He accepts Becker's measurement of 2,005 feet at Virginia City, farther north. Within the Silver City area the amount of displacement fades out southward.

It seems possible that the author in stressing the importance of the pre-mineral and post-mineral periods of movements has given the impression of two distinct and separate periods of activity to what was possibly a much more complex history of movement. Movement of post-mineral age, but belonging to the earlier, pre-topographic period of faulting may, for example, be of greater magnitude than the text suggests. It may also be questioned whether the late faulting expressed by the topography should be placed as far back as the Pliocene. The later fault as mapped follows the base of the scarp very closely and, although the scarp is considerably eroded, there is no apparent retreat of its base in the interstream areas. The upland surface, dislocated by the faulting, is a common feature of Nevada fault block ranges and may well date from the late Pliocene. Definite determination of its age would give a limiting time for the renewal of block faulting, which has played such a large part in forming the topography of the Basin and Range province.

The author's study was principally devoted to the sequence and structure of the rocks and the ore deposits themselves are rather briefly treated. The mineralization of the Silver City district differed from that of the neighboring Virginia district chiefly in that, instead of being concentrated along a single large lode, it was confined to a number of smaller veins that lay along the southward feathering part of the pre-mineral fault. The ratio of gold to silver is higher than for the mines in the Virginia City district and base metal sulphides other than pyrite much rarer. The gangue consists of quartz and calcite with minor adularia and the ore minerals noted are pyrite, gold, silver, electrum, occasional argentite, and rare chalcopyrite.

Secondary enrichment appears to be negligible but productive mining is confined to a shallow zone, the bottom of which is approximately at the same level as the deeper productive workings in the neighboring Virginia City district. No positive evidence against the possibility of deep ore is found. The author does not consider the possibility that the variation of the gold-silver ratio in different parts of the Lode may be the result of primary zonal deposition, which Nolan believes to have taken place at Tonopah.

Wallrock alteration, aside from silicification close to the veins, consists of "the introduction of quartz, calcite, epidote, and pyrite, alteration of the feldspars to calcite and sericite, and the ferromagnesian minerals

to calcite and chlorite." It seems remarkable that no albite should be present in rock alteration of this type.

The author shows the fallacy of the early theory that the ores were deposited close to the surface and demonstrates that the post-mineral erosion of the Comstock region has been more than 2,500 feet, thus confirming Graton's earlier estimate of the depth of mineralization.

The bulletin is a valuable and timely contribution, not only for the determination of the succession and structure in an old but still active district, but as a substantial contribution to the Tertiary geology of Nevada, particularly basin-range structure. One could criticize details here and there; minor faults of expression could have been eliminated by care in revision and editing of the manuscript, and there are a few discrepancies between map and text. The importance of the major results obtained and the promptness of publication, compensate for these minor blemishes. As in all the bulletins of this series, great credit is due to the State Printing Office for the clearness of the illustrations and excellent printing.

H. G. FERGUSON.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

Essentials of Engineering Astronomy. By J. H. SERVICE. Pp. xv + 167. Illus. 33. Cloth 6 × 9. Prentice-Hall, Inc., N. Y. 1937. Price, $2.50.

This should be a welcome companion of the civil engineer, the geologist or the explorer whose only aids in the mapping of a new region are a good transit and a good watch. Its first part of 82 pages deals with those principles of spherical trigonometry and astronomy that underlie the technique of mapping which is developed in its second part of about 60 pages, entitled "Practice." The discussions are brief, but clear and the directions for determining the astronomical factors are definite and comparatively simple. These are treated under the chapter headings: star identification, determination of azimuth, latitude and longitude using Polaris, other stars where Polaris is not visible and the Sun. Descriptions of the use of the striding level, solar attachments and the sextant are briefly outlined and a short account is given of the use of the computing machine. Emphasis, however, is placed on methods requiring only a simple transit and a good watch.

W. S. BAYLEY.

Metasomatische Probleme. (Mount Isa, Rammelsberg, Meggen, Mansfeld, und Künstliche Verdrängung.) By C. SCHOUTEN. Pp. 142; 3 text figures; 174 half tone figures.

This is an elaborate microscopic study of metasomatic processes as illustrated by the ores of Mount Isa, Rammelsberg, Meggen, and Mansfeld. Part of the data regarding Mount Isa was presented in the June-July number of ECONOMIC GEOLOGY, but the discussion of this deposit is by no means duplicated in the two papers.

Metasomatism is defined in the conventional manner and the process is illustrated by many changes which took place during the formation of the minerals. As usual pseudomorphism is the most valuable evidence of metasomatic replacement. The detailed nature of the paper is indicated by the fact that it is illustrated by 174 half tones and three text figures, each of which consists of more than a score of small sketches. Various aspects of the ores of each district are described and discussed; particularly pseudomorphism, gel structure, paragenesis, and finally a review is given of replacement investigations in the laboratory.

Most striking and unusual of the microtextures illustrated are atoll shaped grains formed by partial replacement of pyrite with the outer shells of pyrite grains resisting replacement better than the core.

The origin of the Mansfeld deposits is discussed at some length with a review of proposed hypotheses under four heads.

The conclusions of the author regarding the origin of the deposits may be freely translated as follows. "We are convinced that metasomatism in Rammelsberg, Meggen and Mansfeld has played a predominant role.

"For Mount Isa, Rammelsberg and Meggen we consider the epigenetic formation as hypogene.

"For Mansfeld we have only called special attention to the epigenetic character of the copper ores, and in part also of the lead and zinc minerals, supported by the microscopic study of the ores."

No doubt many American geologists interested in the origin of ores will be pleased at this strong support by a European geologist of the epigenetic origin of the ores of some important districts.

G. M. SCHWARTZ.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.

Sands, Clays, and Minerals (A. L. CURTIS, Box 61, Chatteris, England) is now starting its third volume and is achieving the aim of its founders. The first number appears with 76 pages and 14 articles, most of them written by prominent men. Several are of particular interest to geologists, notably: Nickel in Canada, by A. H. A. Robinson, Ottawa; Mineral Resources of Brazil, by Prof. A. Cownley-Slater; Boron, by

L. Sanderson; Industrial Water Supply, by Prof. E. Morton; Barytes Deposits of Greece, by G. J. Scotis; Mining and Mineral Resources of Tanganyika, by Sir Edmund Teale. These are a worthy group. The number is well illustrated too. We wish it continued success.

An Outline of Geography. By P. E. JAMES. Pp. 475; pl. 24; figs. 182. Ginn & Co. Price $3.00.

An old subject brought up to date and treated in a new way. The Earth's land surface is divided into 8 groups—the Dry Lands, the Grasslands, the Mountain Lands, etc. Under each such heading are discussed rainfall, vegetation, distribution, drainage, land forms, occupance, and culture. Five appendixes deal with the atmosphere, lithosphere, hydrosphere, statistics, and references. These are followed by a section of charts and maps, ten of which are colored. There are many excellent line drawings and block diagrams. It is the most interesting textbook on geography we have read.

Mineralogy, An Introduction to the Study of Minerals and Crystals. By E. H. KRAUS, W. F. HUNT AND L. S. RAMSDELL. 3d Edition. Pp. 638, figs. 812. McGraw Hill, New York, 1937. Price $5.00.

Review notice given in No. 4, p. 529, but authors' names are corrected as above.

BOOKS RECEIVED.

J. D. BATEMAN

Geology of Teslin-Quiet Lake Area, Yukon. E. J. LEES. Pp. 30, pls. 2, map. Can. Dept. of Mines, Geol. Surv. Mem. 203, 1936. Price, 25 cts. General geology; gold placers; silver-lead veins.

Rocky Mountain Oil and Gas Operations for 1936. Pp. 125. Petroleum Information Inc., Denver. Statistical data.

Vermiculite and Bentonite of Tennessee Valley Region. Pp. 51. T. V. A., Div. of Geol., Bull. 5, 1936. Series of papers describing regional occurrences.

Mining Directory-Catalog and Engineers Handbook. Pp. 145. Los Angeles Chamber of Commerce, 1937. Price, $2.00. Very useful handbook with articles on mining and geophysical methods, aerial photography, spectograph, mining law, mineral tables, chemical compounds, weights, measures, mathematical tables and charts.

Geology of Lake Athabaska Region, Saskatchewan. F. J. ALCOCK. Pp. 41, figs. 2, pls. 8, maps 4. Can. Dept. of Mines, Geol. Surv. Mem. 196, 1936. Price, 25 cts. Regional geology of area in which recent large, low-grade, gold deposits have been found in granite.

Report of the Department of Mines, Canada, 1936. Pp. 54. Price, 25 cts.

Lode Gold Deposits of Ymir-Nelson Area, British Columbia. W. E. COCKFIELD. Pp. 78, figs. 8, map. Can. Dept. of Mines, Geol. Surv. Mem. 191, 1936. Price, 25 cts. Descriptions of fissure vein gold deposits.

Mineral Resources of Tennessee, 1936. K. E. BORN. Pp. 102, figs. 3, map. Tenn. Div. of Geol., 1936.

The Van Oil Field, Texas. R. A. LIDDLE. Pp. 82, pls. 1, maps, 26. Univ. of Texas, Bull. 3601, 1936. Detailed structural maps with text.

Resurvey of the Geology and Ore Deposits of the La Plata Mining District, Colorado. E. B. ECKEL. Pp. 40, fig., pls. 2. Proc. Col. Sci. Soc., vol. 13, no. 9, 1936.

Geology and Ore Deposits of the Tincup Mining District, Gunnison County, Colorado. E. N. GODDARD. Pp. 43, figs. 4. Proc. Col. Sci. Soc., vol. 13, no. 10, 1936. Silver-lead-gold; molybdenum-tungsten; iron; interesting structure.

Biennial Report of the State Geologist, Missouri. H. A. BUEHLER. Missouri Geol. Surv., 1937. Includes reports of geological investigations.

Outline of the Mineral Resources of Virginia. W. M. MCGILL. Pp. 81, figs. 2, pls. 16. Va. Geol. Surv., Bull. 47, 1936. Chiefly coal, gold, manganese, building stone.

The Mining Industry of Idaho, 1936. A. CAMPBELL. Pp. 315, pls. 39. Thirty-eighth Ann. Rept. Description of all mines.

The Non-Metallic Mineral Resources of New Mexico and Their Economic Features. S. B. TALMAGE AND T. P. WOOTTON. Pp. 159, figs. 4, pls. 2, map. New Mex. Bur. Mines and Min. Res., Bull. 12, 1937.

Tishomingo State Park, Mississippi. W. C. MORSE AND C. S. BROWN. Pp. 77, pls. 3, map. Miss. Geol. Surv., Bull. 32, 1936. Geologic history and botany.

Spirit Leveling in Connecticut, 1922–35. J. G. STAACK. Pp. 65, fig., pl. U. S. Geol. Surv., Bull. 881, 1937. Price, 10 cts. Statistical.

Geology and Mineral Resources of the Butler and Zelienople Quadrangles, Pennsylvania. G. B. RICHARDSON. Pp. 93, figs. 10, pls. 4, maps 4. U. S. Geol. Surv., Bull. 873, 1936. Price, 45 cts. Coal, oil and gas in Carboniferous strata.

Possibility of New Oil Pools in the Siliceous Lime and Bartlesville Sand in T.23 N., R.10 E., Osage County, Oklahoma. N. W. BASS, W. R. DILLARD AND J. H. HENGST. Pp. 4, fig. U. S. Geol. Surv., Bull. 886–A, 1936. Price, 5 cts. Description of several localities favorable for prospecting.

Gold-Bearing Deposits on the West Coast of Vancouver Island Between Esperanza Inlet and Alberni Canal. M. F. BANCROFT. Pp. 34, map. Can. Dept. of Mines, Geol. Surv. Mem. 204, 1937. Price, 25 cts. Descriptions of auriferous quartz vein and placer deposits.

The Mining Industry of South Dakota. F. C. LINCOLN, W. G. MISER AND J. B. CUMMINGS. Pp. 201, figs. 40, maps 3. S. D. School of Mines, Bull. 17, 1937. Metallic and non-metallic production; mining law; index of mining properties.

Deutsches Bergbau Jahrbuch, 1937. Pp. 376. Wilhelm Knapp, Halle (Saale). Price 10.88 RM. Complete index of all branches of German mining industry.

Canadian Mines Handbook, 1937. Pp. 383. Northern Miner Press, Toronto. Price $1.00. New complete directory of Canadian mines.

Handmaiden of the Sciences. E. T. BELL. Pp. 216, figs. 32. Williams & Wilkins, Baltimore, 1937. Price $2.00. A popular presentation of mathematics; technical knowledge not presupposed. Explains mathematical concepts—probabilities, chance, fourth dimensions, continuity, and discreetness of matter and motion; their usefulness and their sense.

Hydrography of Monterey Bay, California. Thermal Conditions, 1929–1933. TAGE SKOGSBERG. Pp. 151, figs. 45. Trans. Amer. Philos. Soc., Philadelphia, 1936. Paper, 12 × 9½ in. Price $3.00.

Suggestions Concerning Desirable Lives of Research in the Fields of Geography and Geology. Edited by E. S. BASTIN, C. O. DUNBAR, and R. S. PLATT. (Mimeographed, 83 pp.) Nat. Research Council, Washington, Dec. 1936. Covers various fields of geology and geography. Correlation of replies to a circular letter sent out in April 1936. Mostly verbatim quotations.

Illinois Mineral Industry in 1935. W. H. VOSKUIL, A. R. SWEENY, AND W. A. NEWTON. Pp. 62, figs. 8, tables 41. Ill. Geol. Surv., Rept. of Investigations No. 43, 1936. Statistical summary and economic review.

Carbonizing Properties and Petrographic Composition of Clintwood Bed Coal from Buchanan County, Virginia. A. C. FIELDNER, J. D. DAVIS, R. THIESSEN, W. A. SELVIG, D. A. REYNOLDS, F. W. JUNG, AND G. C. SPRUNK. Pp. 34, figs. 19. U. S. Bur. of Mines, Tech. Pap. 570, 1936.

Carbonizing Properties and Petrographic Composition of Pittsburgh Bed Coal from Washington County, Pennsylvania. A. C. FIELDNER, J. D. DAVIS, R. THIESSEN, W. A. SELVIG, D. A. REYNOLDS, G. C. SPRUNK, AND F. W. JUNG. Pp. 33, figs. 21. U. S. Bur. of Mines, Tech. Pap. 571, 1936. Price, 10 cts.

Analysis of New Mexico Coals. Pp. 112, fig. U. S. Bur. of Mines, Tech. Pap. 569, 1936. Price, 15 cts.

SCIENTIFIC NOTES AND NEWS

H. E. McKinstry returned to New York from a short professional trip to London in July, then went to Wallace, Idaho, and spent the latter part of the summer doing geological work in the West.

Henry B. Kummel, after a service of more than 40 years, has retired from the position of State Geologist of New Jersey and director of the Department of Conservation and Development, but will continue as a consulting geologist of the State. Charles P. Wilber, State Forester, succeeds him as director of the Department of Conservation and Development, and Meredith E. Johnson, formerly Dr. Kummel's assistant geologist, becomes State Geologist.

F. E. Calkins is engaged in mine examinations for Frank Eichelberger, with headquarters at 209 Tabor Bldg., Wallace, Idaho.

F. L. Hess, mineralogist of the U. S. Bureau of Mines, is on a trip to the Far East.

W. R. Chedsey, for 21 years professor of mining at the School of Mineral Industries at Pennsylvania State College, has been appointed director of the Missouri School of Mines and Metallurgy at Rolla, Mo.

Guy N. Bjorge, general manager of Homestake Mining Co., Lead, S. D., was director of the annual convention and exposition of the Western Division of the Am. Mining Congress held in Salt Lake City, September 7 to 10.

John M. Lovejoy, President of Seaboard Oil Co., Amiranian Oil Co., and Inland Exploration Co., sailed from New York with his family, July 18, on a month's vacation in Europe.

Hubert G. Schenck, of Stanford University, sailed July 20 for a year's field work in the employ of Amiranian Oil Co. and Inland Exploration Co. in their concessions in Iran and Afghanistan.

Frederic B. Loomis, professor of geology at Amherst College, died suddenly while on a fishing trip in Alaska in July.

The Society of Economic Geologists will hold their annual meeting in Washington at the time of the Geological Society of America meetings, December 28–30. The Program Committee will be glad to receive papers for presentation at the scientific sessions. Titles may be sent to T. B. Nolan, U. S. Geological Survey, Washington, D. C., or given to other members of the Committee. In accordance with the practice established at the last meeting, abstracts should be provided, although they need not be forwarded until December 1.

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